Sustainability Assessment of a Sustainable Innovation for the Aviation Industry: Case Study of Bio Composites for Aircraft Interiors

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Master Thesis

Delft University of Technology
MSc Porogramme in Management of Technology
Collins Aerospace (K.F.I. B.V)

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Executive Summary

The current impact of the aviation industry on climate change poses little choice for aviation companies but to invest in sustainability. One way to do this is to develop and implement sustainable innovations in aircraft. However, the question is how it can be validated whether an innovation is sustainable. To do so, this research uses sustainability assessment methodologies. In particular, it investigates, how the integration of sustainability assessment tools can support the decision-making process regarding investment in sustainable innovation. As a result, this thesis presents the methodology for the sustainability assessment of sustainable innovation for aircraft while using two tools - Life Cycle Assessment (LCA) and Cost-Benefit Analysis (CBA). The first one is to assess the environmental impacts of an innovation, the second one is to determine its financial and also social implications.

The chosen sustainable innovation, upon which the case study is developed and the methods are tested, is the bio composite material for usage in aircraft interiors. In particular, the viability of replacing conventional composites in Boeing 787-8 aircraft business class seats with bio composites is considered. The thesis is conducted in collaboration with Collins Aerospace, which is the manufacturer of products for aircraft; therefore, examines the usage of more sustainable materials. Before realizing sustainability assessment, the technology is analysed using theoretical frameworks. In particular, the analysis is developed on technology drivers, challenges, and the current stage of development in the aviation and automotive industry. After that, the specific bio composite suitable for aircraft interior - geopolymer panel created in an EU project - is chosen for further sustainability assessment. Next, the case study includes the environmental assessment (comparative, fast-tracked LCA) and economic assessment (CBA) of the chosen material. The LCA concludes that usage of the bio composite reduces the carbon footprint and energy requirement by 38%, however, increases the water consumption by 47%. The result from CBA is that due to the lower weight of bio composite material, an airline can save €3382±338 on 1 out of 18 business class seats during 5 years of aircraft operation; hence, this is by how much 'bio seat' can be more expensive to be still profitable. Therefore, the case study proves that bio composites are better than conventional composites from an environmental and economic point of view.

The case study presents that sustainability assessment provides information valuable for the decision-making process. Integrating environmental and economic assessment shows a bigger picture and broadens the perspective. Additionally, the analysis of technology based on theoretical frameworks provides important insights for both, decision-making and sustainability assessment. Also, the integration of LCA and CBA tools is concluded to be suitable for this purpose and the methodology is described. The problems associated with such tools combination are discussed, where double-counting is the challenge discovered in the study. In addition, the issues stated in the literature are evaluated, and the propositions on how these challenges can be overcome are indicated.

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List of Abbreviations

ACARE	Advisory Council for Aviation Research and Innovation in Europe
BC	Benefits from saved Carbon fees
BE	Benefits from saved Environmental costs
BF	Benefits from saved Fuel costs
CBA	Cost-Benefit Analysis
CF	Carbon Footprint
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CO2	Carbon Dioxide
CSIR	Council for Scientific and Industrial Research
EIA	Environmental Impact Assessment
E	Energy
EU	European Union
EU ETC	European Union Emissions Trading System
EP	Epoxy
FAR	Federal Acquisition Regulation
fCBA	financial Cost-Benefit Analysis
FRP	Fiber Reinforced Plastic
GHG	Greenhouse Gases
ICAO	International Civil Aviation Organization
IETA	International Emissions Trading Association
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
MCDA	Multi-Criteria Decision Analysis
MFA	Material Flow Analysis
sCBA	social Cost-Benefit Analysis
OEM	Original Equipment Manufacturer
OEW	Operating Empty Weight
PC	Carbon Prices
PE	Environmental Prices
PEI	Polyetherimide
PF	Fuel Prices
PFA	Perfluoroalkoxy alkane
PLA	Polyactic acid
PP	Polypropylene
RQ	Research Question
SAF	Sustainable Aviation Fuel
TOW	Total Operating Weight
TSFC	Total Specific Fuel Consumption
US	United States

1 INTRODUCTION

The aviation industry has a significant impact on the environment as it accounts for approximately 2.5% of global CO2 emissions and for other non-carbon related emissions that contribute to climate change (Pinheiro Melo *et al.*, 2020). Despite the number of innovations that improved fuel efficiency, the rising number of flights and passengers contributes to greater carbon footprints of the aviation industry. There is evidence of an occurring gap - the pace of improvement of efficiency is expected to reach annually 1,5%, while the growth of the air traffic demand is about to reach 4,5% annually (ICAO, 2016; Pinheiro Melo *et al.*, 2020). Moreover, International Civil Aviation Organization (ICAO) predicted that the emissions could grow by 300%-700% by 2050 (Bachmann *et al.*, 2017). Therefore, the actions are taken by regulators, to reduce emissions of the sector which can be seen by including the aviation sector in the EU Emissions Trading Scheme (Bachmann *et al.*, 2017).

On the other side, the aviation industry is considered to be the most challenged industry with sustainability issues and environmental impact (Abdi *et al.*, 2022). Although nowadays sustainable innovations in the aviation industry are crucial because, without these, future emission goals might be hard to reach. However, the question is how aviation companies can decide which innovations to pursue. In particular, how can they assess whether an innovation is good from an environmental point of view and can also bring economic value for them? To answer that, the sustainability assessment can play a role and help in such a decision-making process. There are large numbers of tools for the sustainability assessment; however, for the purpose of this research, the chosen are the Life Cycle Assessment (LCA) for measuring environmental impacts, and Cost-Benefit Analysis (CBA) for investigating mainly economic, but also social implications. Additionally, CBA is evaluated on what is the impact of including environmental/social implications in economic assessment. Not many studies are combining LCA and CBA methods for the evaluation of innovation viability. Thus, the knowledge gap for the evaluation of the combination of these two methods is recognized. Moreover, no research was found which is integrating LCA and CBA tools to assess a sustainable innovation specifically used in aircraft. Hence, there is a knowledge gap in the methodology of how to do such an assessment for aircraft products.

As a sustainable innovation for the aviation industry, the bio composite materials for aircraft interiors are being investigated, where the integration of sustainability assessment tools is tested. That innovation was chosen because of the recognized environmental and economic potential of the technology. The environmental, since the natural fibers are currently being discussed to be more environmentally friendly than synthetic fibers in production and end-of-life stage (Duflou *et al.*, 2014). The economic, since these are lightweight materials, which can contribute to a lower fuel burn of an aircraft (Vidal *et al.*, 2018). Hence, it can result in both, financial profits for airlines owning a product made from bio composites and lower emissions during a flight. Additionally, Collins Aerospace, the collaborating company, manufactures products for aircraft interiors; therefore, the research on innovative materials is consistent with their field and interest. Lastly, bio composites are widely investigated in the literature for automotive industry usage; however, little attention is paid to investigating these materials for the utilization of it in aircraft interiors. Therefore, another knowledge gap is recognized which will be answered via a case study.

Sustainability is usually discussed in three areas which are commonly called pillars of sustainability, namely environment, economy and society (Hoogmartens *et al.*, 2014). According to Eikon, 2017, the environmental aspect includes resource use, emissions and innovation. When it comes to the economic aspect, this one is associated with bringing economic value to the business sector which contributes to sustainable development (Ekins & Vanner, 2007). Lastly, the social aspects are about human well-being where the reduction of air pollution plays a big role (Hoogmartens *et al.*, 2014). In the context of that research, the focus is on two pillars of sustainability - environment and economy. However, the social aspect is implicitly integrated into the economic assessment where the social implications on human welfare related to better or worse air quality are monetized and taken into account.

The Master Thesis is conducted with the company Collins Aerospace. Therefore, the problem statement is separated into the industry problem and academic problem. Additionally, it is transdisciplinary research since it combines knowledge from multiple disciplines to jointly create new knowledge. In the context of this study, the transdisciplinarity stems from the fact that the research combines knowledge from innovation, environmental and economic studies. All three disciplines act together in order to answer the research question.

1.1. PROBLEM DEFINITION

The sustainability assessment is a process which can be approached from an academic and business perspective. In this work, these two are combined, and the industry problem is approached using academic frameworks. Hence, the case study results are answering the industry, but the integrated methods used there contribute to academic research.

1.1.1. INDUSTRY PROBLEM

The industry problem is practical in nature and in the case of that research, it is the problem of investigating the potential of creating sustainable products for aircraft interiors. In particular, how the sustainability of innovation can be assessed, which tools can be used, and which methodology is suitable to provide information for decision-makers.

Additionally, Collins Aerospace, as well as other actors in the industry, experiences challenges to create economic profits from investments in sustainable innovations. In the case of this company, the main focus is on aircraft interiors. Therefore, it was recognized in the preliminary research that sustainable innovation that has the potential for creating commercial value is using lightweight materials in aircraft interiors. In particular aircraft seats are the crucial products in which conventional materials could be replaced with bio composites. This particular product is chosen due to the current business model that occurred in the aviation industry and which was indicated by Collins Aerospace. According to personal communication with Collins Aerospace employee (17.02.2023) and Staff, 2006, it has been noticed that aircraft seats are changed very frequently, every 4-7 years, which is more than they are designed for. This happens due to often cabin reconfiguration of the cabin interiors and short leasing contracts. For instance, airlines of higher quality are ending leasing contracts after a few years as they want to lease newer aircraft with more efficient engines. In such a situation, the aircraft is leased to a different airline which is changing seats due to its individual standards and colours. Therefore, there is pressure to use recyclable materials in seating products as these are changed frequently. In addition to that, the aircraft interiors contribute between 10-20% to overall environmental impact during the aircraft lifecycle (Bodell, 2023). Therefore, new cabin solutions are looked for. Additionally, business class seats are the heavies; hence, the industry is focused on the weight reduction of that product without the deterioration of passenger experience.

Looking at the occurred in the industry problems, the needs were identified and it was concluded that innovative, lightweight materials will be looked into. In particular, an emerging technology for aircraft interior - bio composite material. Firstly, the analysis of the technology will be done using theoretical frameworks. Further, the potentials of the technology need to be investigated. In particular, the environmental impacts of replacing existing materials with bio composites in the current seating products of Collins Aerospace will be calculated. Here, it is desired to assess environmental benefits not only by looking at carbon footprint but also by combining it with resource usages such as water consumption and energy usage. Secondly, it is necessary to assess whether such a replacement has the potential to bring economic value to the company. The potential is recognized as bio composites can be lighter than conventional materials which will contribute to lower fuel burn; therefore, it will be attractive for airlines that are the clients. However, a deeper analysis should be done in order to confirm or reject that statement.

1.1.2. Academic Problem

From an academic angle, the sustainability assessment field is explored. In particular, academia presents many tools for sustainability assessment; however, the integration of these tools is discussed to be challenging. This is because many tools are designed to answer the question regarding only one pillar of sustainability. However, to answer two or even three pillars, tool integration is usually necessary. But because of different boundaries, time spans and focuses, the task of methods combination in the form of a case study is not widely developed in the literature. Therefore, there is a need to present the test case for methods integration.

For the purpose of this exercise, the combination of environmental and economic impacts is necessary to answer the industry problem. Therefore, the two tools which are identified to be possibly integrated - LCA and CBA are used. This combination will be further evaluated by pointing out the approached challenges. Additionally, using an academic approach the chosen technology will be first investigated. There are presented frameworks in the innovation study field which can serve for an innovation analysis. How these can help for the further sustainability assessment is also a question that is not answered. Therefore, instead of regular business market analysis, theoretical frameworks are used to analyse the technology to get insights for further sustainability assessment.

Additionally, the problem is transdisciplinary. It is using the knowledge from innovation studies and combining it with environmental assessment methods and economic implications. There are recognized many interests from different stakeholders. Using the Joint Problem Framing in transdisciplinary research the problem can be framed as the following (Pearce & Ejderyan, 2020). On one side, the company producing products for aircraft (e.g., Collins Aerospace) needs to have profits, so it wants to innovate to be competitive and sustain customers. On the other side, a customer wants affordable products and needs to choose more sustainable solutions because of incoming regulations. Hence, the government is another stakeholder, since ICAO commits to the goal of Net Zero 2050 and the EU includes aviation in the trading scheme. Lastly, science is mainly investigating technologies from an environmental point of view; however, in such transdisciplinary research, economic assessment is essential.

All the mentioned contributions will be possible to be generalized for different sustainable innovations within aviation or different industries. The two tools of sustainability assessment, LCA and CBA, will be assessed on how they might help in the decision-making process regarding investment in sustainable innovation.

1.2. Research Objective and Research Question

The objective of the paper is *to find out how the sustainability assessment tools, LCA and CBA, can together aid in making informed investment decisions regarding sustainable innovation in the aviation industry*. The **research question** with its sub-questions are specified. There is one, general, research question that is supported by four more detailed questions that are aligned with the research flow.

RQ1 - How can integrated sustainability assessment tools support the decision-making process regarding the development of sustainable innovation for the aviation industry?

- RQ1.1 - How can innovation theoretical frameworks provide insights for the sustainability assessment of bio composite technology?
- RQ1.2 - How can a Life Cycle Assessment (LCA) and Cost Benefit Analysis (CBA) be applied to assess the sustainability of a product for aircraft usage?
- RQ1.3 - What challenges and opportunities are associated with integrating LCA and CBA sustainability assessment tools?
- RQ1.4 - What factors can impact the results from the sustainability assessment tools?

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LITERATURE STUDY

The literature overview starts with a description of the 'sustainability assessment' term. That section further investigates which methods and tools are indicated by the literature as suitable for sustainability assessment. Next, sustainable innovations for aircraft are looked into, and the part is summarized with the most discussed sustainable innovation in the aviation industry. Lastly, bio composites are studied in the literature, which is the chosen sustainable innovation for the case study.

2.1. SUSTAINABILITY ASSESSMENT

In this section, first, the definition of sustainability assessment and its purpose were investigated. Next, the methodologies/tools that can be used to develop sustainability assessments were looked into. In addition to that, the articles' conclusions from the integration of these tools were summarized.

2.1.1. SUSTAINABILITY ASSESSMENT AS A DECISION-MAKING TOOL

Sustainability has three components that are widely accepted in the literature: environment, economic and social (Ekins & Vanner, 2007). The sustainability assessment is defined as "any process that directs decision-making towards sustainability" (Bond *et al.*, 2012). Other studies such as Buytaert *et al.*, 2011; Myllyviita *et al.*, 2017; Waas *et al.*, 2014 confirm that sustainability assessment supports the decision-making process. It provides decision-makers with an evaluation of which actions should be taken to make society more sustainable (Buytaert *et al.*, 2011; Ness *et al.*, 2007). Moreover, Waas *et al.*, 2014 adds that sustainable assessment plays a significant role in strategy and addresses three challenges: interpretation, information-structuring, and influence. Ness *et al.*, 2007 says that in order to do a transition towards sustainability, the goals must be assessed which is why sustainability assessment become a rapidly developing area. The research of Ekins and Vanner, 2007 presents also the value of sustainability assessment for companies. The authors argue that the business sector needs to create economic value, but also at the same time should sustainably use natural resources and the environment. Therefore, to achieve these, there is a need for a tool which helps business to monitor and manage these aspects. In the literature, sustainability assessment is presented as the process which meets the needs of current businesses. Lastly, the papers Buytaert *et al.*, 2011; Ness *et al.*, 2007; Waas *et al.*, 2014 say that it is a complex exercise. The author say that it has many uncertainties and associated risks; hence it is considered by scholars as something which is "measuring the immeasurable" (Waas *et al.*, 2014). In particular, the complexity stems from the fact that sustainability itself is a multidimensional subject (Buytaert *et al.*, 2011).

2.1.2. METHODOLOGIES REVIEW

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According to Ness *et al.*, 2007, the number of tools that can be used for the assessment of sustainability has grown, and the old tools have developed. The literature which assesses these tools was looked into and the conclusion from each of these was made. In particular, six different papers were looked into and the methods that were repeated are further analysed. These are Life Cycle Assessment (LCA), Cost-Benefit Analysis (CBA), Environmental Impact Assessment (EIA), Life Cycle Costing (LCC), Multi-Criteria Decision Analysis (MDCA), Material Flow Analysis (MFA), and Risk Analysis. The papers and the analysis methods in each research are presented in Table 2.1.

Table 2.1.: The literature on sustainability assessment methods and tools

	LCA	CBA	EIA	LCC	MDCA	MFA	Risk Analysis
Buytaert *et al.*, 2011	x	x	x				
Dong *et al.*, 2018	x	x		x			x
Myllyviita *et al.*, 2017	x	x		x	x	x	
Ness *et al.*, 2007	x	x	x	x	x	x	x
Hoogmartens *et al.*, 2014	x	x		x			
Finnveden and Moberg, 2005	x	x	x	x		x	x

LCA

LCA is a standardized ISO 14040 method which is assessing the environmental impacts of a product or service (Myllyviita *et al.*, 2017). It allows for the assessment of many impacts such as carbon footprint, toxicity, acidification etc. It can be applied to identify the impacts of the assessed system or to compare different alternatives from an environmental point of view (Dong *et al.*, 2018). According to Buytaert *et al.*, 2011 which evaluated six different tools, LCA is "one of the strongest players" from the tools with an environmental focus. Their analysis showed that it has established and transparent guidelines. They also mentioned that it is product oriented method which is confirmed by Buytaert *et al.*, 2011; Dong *et al.*, 2018; Hoogmartens *et al.*, 2014; Ness *et al.*, 2007. The theoretical background of LCA is described in chapter 3 in section 3.3.1.

CBA

CBA is a method that based on monetized values compares benefits with costs and provides an answer whether a project is worth pursuing or not (Myllyviita *et al.*, 2017). The authors say that typically it includes solely monetary values; however, incorporating the concept of sustainable development is possible. This can be done by the valuation of environmental impacts. Therefore, contrary to LCA, CBA has an economic focus (Buytaert *et al.*, 2011) with an emphasis on socio-economic impacts (Dong *et al.*, 2018). The literature agrees that this method is more project-oriented (Buytaert *et al.*, 2011; Dong *et al.*, 2018). It is an established and utilised tool, popular among decision-makers (Buytaert *et al.*, 2011; Dong *et al.*, 2018). The theoretical background of CBA is described in chapter 3 in section 3.3.2.

EIA

EIA evaluates the potential environmental impacts and considers three pillars - environmental, social and economic issues (Buytaert *et al.*, 2011). The purpose of the methods is to identify, predict, evaluate and mitigate social, biophysical and other impacts before the decision on the development is made (Buytaert *et al.*, 2011). It is widely used by regulations, also in the EU (Buytaert *et al.*, 2011; Ness *et al.*, 2007). According to Hoogmartens *et al.*, 2014, both LCA and CBA start from EIA; however, both also go further. In particular, LCA looks not only at the product impacts but also at the whole life cycle impacts. CBA in addition to EIA puts a monetary value on the environmental impacts.

LCC
LCC is claimed to share the same principles as the regular LCA but looks at both social impacts and cost flows (Buytaert *et al.*, 2011). Ness *et al.*, 2007 say that a method is an economic approach that includes the product, process or activity costs and discounts them over a lifetime. The tools that include life cycle costing and environmental costs are Full Cost Environmental Accounting and Life Cycle Cost Assessment (Ness *et al.*, 2007). Myllyviita *et al.*, 2017 considers LCC as the life cycle method which is associated with LCA; however, does not further evaluate the method. Contrary to CBA, LCC is mostly used for product-related assessment (Hoogmartens *et al.*, 2014). Hoogmartens *et al.*, 2014 presents an example that can help determine which method is more suitable for research. *If the study of a road focuses on the negative externalities that are caused by exhaust gases, the road is taken to be a product [and the LCC approach is better]. However, when investigating whether a road should be constructed or not, the construction of the road can be seen as a project and a CBA would be appropriate.* According to Finnveden and Moberg, 2005, LCC and CBA can be similar when applied to a product; however, benefits typically are not included in LCC.

MDCA
MDCA is a group of methods serving for decision-making process (Myllyviita *et al.*, 2017). It is to identify and select alternatives which are preferred when a complex problem is approached. The method seeks the trade-offs and incorporates qualitative and quantitative data (Ness *et al.*, 2007). According to Myllyviita *et al.*, 2017, MDCA has the greatest potential from the tools that they researched as it is flexible and transparent. However, the authors also say that using solely MCDA is not advised as it requires inputs from other tools and methods to properly assess impacts. That is why as Ness *et al.*, 2007 categorised it in their paper, the method is an integrated tool.

MFA
MFA is a family of methods; however, the most discussed is Substance Flow Analysis (SFA) (Finnveden & Moberg, 2005; Myllyviita *et al.*, 2017; Ness *et al.*, 2007). It is performed through the phases of the life cycle and investigates the inflows and outflows of materials/substances related to a process (Myllyviita *et al.*, 2017; Ness *et al.*, 2007). It can be performed regionally or globally and aims to identify the problems in the flow of substances (Ness *et al.*, 2007).

RISK ANALYSIS
Risk analysis is named as 'risk-based decision analysis' by Dong *et al.*, 2018, and as 'risk assessment' by Finnveden and Moberg, 2005. Risk assessment covers many different types of assessment (Finnveden & Moberg, 2005). Dong *et al.*, 2018 defines it as a tool to evaluate policies and assess performance for systems and services that are complex and in which the potential risk exists. Ness *et al.*, 2007 say that it is an assessment of potential

damages. It is often chosen for project-oriented analyses such as the evaluation of food safety and mitigation policies against natural diseases (Dong *et al.*, 2018).

TOOLS INTEGRATION

As can be seen, various tools can be used; however, these can be also combined, depending on the exercise requirements. According to Dong *et al.*, 2018, CBA is often used as a decision-making tool; however, environmental aspects are not well addressed there, which makes it difficult to properly support decisions towards sustainability. The research says that LCA is the response to that issue and the results from LCA can provide valuable information to support decision analysis tools like CBA. Hoogmartens *et al.*, 2014 point out the issues that are associated with combining LCA and CBA. The authors say that LCA evaluates the whole life cycle of a product, while CBA investigates the duration of a project. Further, the covered life stages, life span, metrics and system boundaries are different, which needs to be taken into account when realizing such an exercise. Dong *et al.*, 2018 mention those issues as well by saying that the focus is on a product in LCA, while on a project in CBA. However, the authors also say that recently the term "product" is used more broadly to address services, sectors, and cities. Moreover, Dong *et al.*, 2018 support combining methods by stating that the mentioned discrepancies can allow obtaining a bigger picture of the decision consequences; however, should be transparently integrated. For instance, geographical boundaries should be clearly identified, as from the LCA perspective all the emissions should be included; however, from the CBA point of view, only the ones concerning the location of a project (Dong *et al.*, 2018). Additionally, consistency in discounting is necessary when integrating LCA and CBA.

Despite discrepancies, few studies combine LCA and CBA. For instance, Møller *et al.*, 2014 used LCA to calculate the carbon footprint of biofuels and these were monetized and integrated into traditional CBA. Moreover, Jones *et al.*, 2018 quantified emissions of train transport service which was further monetized and used in CBA by calculating NPV. Therefore, Dong *et al.*, 2018 conclude that there are ways to combine the two methods and examples are presented in the literature; however, caution and transparency are needed when integrating these. Moreover, the literature review did not find any work which would integrate LCA and CBA in the assessment of sustainable innovation for the aviation industry which is used in an aircraft.

When it comes to different combinations, Bare, 2006; Flemström *et al.*, 2004; Olsen *et al.*, 2001, concluded that combining LCA and risk assessment methods is not suitable because these have different scopes and aims. In addition, the integration of LCA and LCC is promising. Hoogmartens *et al.*, 2014 argue that environmental LCC (eLCC) with environmental (eLCA) or social LCA (sLCA) can be in a complementary way used together. The combination of these tools leads to the Life Cycle Sustainability Assessment (LCSA) which includes all three pillars of sustainability. The authors also suggest that LCA and LCC are more suitable combinations than the LCA and CBA. However, Dong *et al.*, 2018 oppose it by saying that the mentioned obstacles for LCA and CBA integration would need to also be conquered for combination of LCA and LCC. Moreover, decision-makers are mostly using CBA; therefore, persuading them to use a new tool might be a challenge.

2.2. Sustainable Innovations for Aircraft

Firstly, the literature about innovation and sustainable innovation is looked into to define the further explores topic. Next, the innovation theoretical frameworks are researched to conclude how an innovation can be analysed using literature streams and which factors can impact technology development. Lastly, the discussed in the literature sustainable innovations in the aviation industry are in detail presented.

2

2.2.1. Sustainable Innovation

Innovation is described as a technology that enables value creation, shapes the future of the industry, improves competitiveness, efficiency, and profitability of the organization as well as improves sustainable development and operational capabilities (Kurt *et al.*, 2013; Mousavi & Bossink, 2017; Pereira *et al.*, 2021; J. Utterback, 2004). According to Ortt *et al.*, 2010, an invention of new technology is the first time the technical principle of such a category is presented and mastered. However, unlike the invention, innovation requires implementation and diffusion (Manual, 2018). This is because as Schroeder *et al.*, 1986 say "invention is the creation of a new idea" when on the contrary innovation is "the development and implementation of a new idea" which could be a product, new technology, arrangement or organizational process.

When it comes to innovation classification, it is usually categorized in four different ways: product versus process innovation, radical versus incremental innovation, architectural versus component innovation, and competence-enhancing versus competence-destroying innovation (Schilling, 2020). This classification is similar according to other authors such as Kurt *et al.*, 2013; Manual, 2018; Niine *et al.*, 2015; Oke, 2007; Pereira *et al.*, 2021; however, the last one is sometimes omitted. A very common distinction is between radical and incremental innovation. Incremental changes are continuous and regular competence-enhancing modifications, where the current production system and existing networks are preserved and value is regularly added to the current system. On the other hand, radical innovations are competence-destroying where the existing system or components are replaced (Mousavi & Bossink, 2017).

When it comes to the definition of **sustainable innovation** the literature voice is the following. According to Bossink, 2013; Mousavi and Bossink, 2017, sustainable innovation is the development of new capabilities at the company that helps "to sustain, improve and renew the environmental, social and societal quality of its business processes and the products and services these business processes produce". Additionally, Hockerts and Wüstenhagen, 2010 includes also economic value in the term definition. In his point of view, sustainable innovation is the discovery and exploitation of economic opportunities which has its origin in market disequilibrium and initiates the system change towards an increased socially and environmentally sustainable state. Further, to asses innovation sustainability, most of the approaches are based on life cycle analyses such as life cycle emission assessment and life cycle costs (Calado *et al.*, 2019; Pohya *et al.*, 2018; Rohacs, 2022).

In the matter of the connection between sustainable innovation and financial performance, researchers are trying to find a relationship. However, the answer in the literature is not straightforward. The authors Bansal and Gao, 2006; Dangelico and Pujari, 2010 conclude that environmental innovations are the key factors for financial growth.

Abdi *et al.*, 2022 found that companies' participation in environmental and social initiatives is positively and significantly rewarded by higher financial efficiency. Also, Hart, 1995; Porter and Van der Linde, 1995 are arguing that such innovation enables firms to save operating costs or reuse the materials via recycling. Their reputation is then better; therefore, they can exploit premium pricing and increased sales (Bansal, 2005; Christmann, 2004). On the other side, according to Link and Naveh, 2006, sustainable innovations do not always contribute to improved financial performance. Aguilera-Caracuel and Ortiz-de-Mandojana, 2013 did not find that green innovative companies are performing financially better than non-green innovative firms. However, they also discovered that when focusing solely on green innovative firms, the intensity of environmental innovations is positively related to firm profitability. Therefore, it can be concluded that the researchers do not agree with the fact that sustainable innovation contributes to the firm's financial performance.

2.2.2. THE INNOVATION LITERATURE STREAMS

There are four literature streams on innovation which can be identified: (1) evolutionary economics, (2) network economics, (3) institutional theory and (4) innovation adaption and diffusion. Each of the streams is based on different literature and determines the factors that affect the adoption of an innovation. In further work only the third and fourth streams are used since are determined to be most appropriate for the analysis; however, to present the background on innovation literature streams here all are discussed.

Firstly, the **evolutionary economics** has its origins in papers of Anderson and Tushman, 1990; J. M. Utterback and Abernathy, 1975. The work of J. M. Utterback and Abernathy, 1975 proved that the innovation process change when a firm grows. Anderson and Tushman, 1990 proposed an evolutionary model of technological change where technological breakthrough initiates an era of radical innovations, further one dominant design emerges which then goes through incremental changes. Hence, according to van den Bergh *et al.*, 2006, it is a theory that proposes that economic processes structurally change, including innovation. In this approach, there are no specific factors or actors that contribute to the adoption of technology.

The second theoretical approach is the **network economics** where the main authors are Farrell and Saloner, 1985; Katz and Shapiro, 1985. According to Katz and Shapiro, 1985, network economics is characterized by the products of which the "utility that a user derives from consumption of the good increases with the number of other agents consuming the good". Hence, the decision on adoption depends upon the adoption decision of other actors.

The third literature stream discusses the **institutional theory** where the research of DiMaggio and Powell, 1983 contributes significantly. The paper argues that organizations when attempting to change become increasingly similar. The authors also indicate three pressures leading to this outcome: coercive, mimetic and normative. According to the DiMaggio and Powell, 1983; Latif *et al.*, 2020, coercive pressures are created by stakeholders such as governmental entities, customers and suppliers. Mimetic pressures are from competitors and stem from the fact that organizations are copying competitors due to uncertain situations. Lastly, normative pressures are from values, norms, standards and expectations which are present in an organization. Moreover, Latif *et al.*, 2020 define the concept of institutional theory by saying that it "suggests that companies' social, environmental and economic performances are greatly affected by the institutional environment in which a company operates." The authors conclude that institutional pressures are the factors that stimulate the culture and organizational norms which encourages the introduction of environmental practices.

Lastly, the **innovation adoption and diffusion** is the theoretical approach discussed where the work of Rogers, 1965 is very influential. The author stated that innovation adoption is a process, where some people are more apt to adapt to emerging technologies and some are more resistant. He also presented the S-curve, which is an adoption of an innovation plotted over time. This is because he concluded that different people adopt technology at different stages; however, it always follows the same pattern of the S-curve. It means that the distribution rises slowly in the beginning, then accelerates and ends with an again slower pace of adoption. Based on Roger's S-curve, Ortt *et al.*, 2010 also investigated the pattern of technological development. In the pattern analysis, the unit of focus is on the generic product where the boundary is the cluster of organization. Ortt *et al.*, 2010 concluded that the pre-diffusion phase is divided into two, the innovation and adaptation phases. The three milestones define it: the invention, the first introduction, and the start of large-scale production and diffusion. The model is presented in Figure 2.1. Additionally, it is argued by Geels, 2002 that technology can be analysed on multiple levels which helps to understand the dynamics of sociotechnical changes. An adapted perspective of Ortt, 2022 shows that not only pattern level (a patchwork of regimes, meso-level at Geels, 2002) can be discussed in regards to innovation, but also project or discipline level. At the discipline level (landscape, macro-level at Geels, 2002), the focus is on a discipline set of generic technologies, where the whole industry is a boundary. At the project level (novelty, micro-level at Geels, 2002), the unit of focus is the product version, where the organization is a boundary. According to Ortt, 2022, for such an analysis, the stage-gate framework is suitable which was presented for the first time by Cooper, 1990.

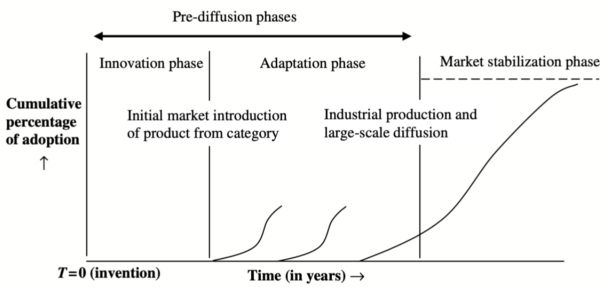

Figure 2.1.: The pattern of development and diffusion of high-tech product categories by Ortt *et al.*, 2010

2.2.3. Sustainable Innovation in the Aviation Industry

In the context of aviation, sustainability aspects in every stage of the life cycle will determine the success of future aircraft systems and affect their potential for environmental impact reduction (Pinheiro Melo *et al.*, 2020). According to Lee and Mo, 2011, the social awareness concerning the impact of aviation on climate change was historically not sufficiently high to actively invest in sustainable technologies. However, later publication of Qiu *et al.*, 2021 says that sustainable development is becoming essential in the path for green aviation and business strategies gradually are promoting development for a better future. The authors also state that because the aviation industry is technology-intensive, innovations are the key to promoting green aviation.

According to Ryley *et al.*, 2013, the aviation sector is considered to be socially and economically sustainable, but there is a concern about environmental sustainability because of climate change impacts. Therefore, in most of the papers when addressing sustainability innovation in the context of aviation, the environmental impact is the main focus. In particular, the aim is to mitigate the negative impact of the aviation sector on the environment. Based on the chosen set of papers presented in Appendix A in Tables A.2 and A.3, the most discussed sustainable innovations in the aviation industry were determined. The results are presented in Table A.1 in Appendix A.

Based on that analysis the most commonly mentioned innovations are the following:

1. Biofuel (with score 12/15),
2. Lightweight Materials (with score 9/15),
3. Ultra-high Bypass Turbofan Engine (with score 7/15).

The results of this part of the literature study show that the further case study on lightweight bio composite materials is justified to be the topic that is considered sustainable innovation in the aviation industry. Even though biofuels are more commonly discussed in the chosen set of the literature on sustainable innovation, lightweight materials are also considered a technology that has a positive impact on the environment. Moreover, is more interesting to interested stakeholder - Collins Aerospace - due to their business profile.

2.3. BIO COMPOSITES

The last part of the literature review concerns the topic on which the case study is developed. The reason for choosing that sustainable innovation specifically for the case study is presented in the Introduction.

To begin, composites are materials that consist of more than one chemically distinct constituent (Arockiam *et al.*, 2018; Sathishkumar *et al.*, 2014). Hence, one composite material can consist of many sub-materials which is explained in detail in section 4.1. In particular, the fibre-reinforced polymers are investigated, where fiber is the reinforcement and polymers are the resin, called also a matrix. Bio composites contain fibre reinforcement made from natural sources (Arockiam *et al.*, 2018). Additionally, some papers also investigate bio-based resins instead of polymer resin (Bachmann *et al.*, 2017). The main reason behind exploring composite materials is the big potential for weight reduction while at the same time maintaining structural integrity (Ranasinghe *et al.*, 2019). This is because lightweight designs lead to lower fuel consumption and consequently, lower emissions (Bachmann *et al.*, 2017). Currently, the commonly used composites in the aviation industry are CFRP (Carbon-fiber-reinforced polymers) or Glare (aluminium glass fibre composite) (de Haan, 2007; Ranasinghe *et al.*, 2019). According to Arockiam *et al.*, 2018, common fibres are carbon, glass and Kevlar. However, all of the mentioned are synthetic fibres which bring concerns in terms of high production environmental impact and poor recyclability (Duflou *et al.*, 2014).

2.3.1. Types of Bio Composites

When it comes to natural fibers, the full overview of the natural fibers done by Mussig and Slootmaker, 2010 is shown in Appendix B on Figure B.1. However, in particular for the automotive industry, Barth and Carus, 2015 investigated flax, hemp, jute and kenaf fibers. Arockiam *et al.*, 2018 did the research on ramie, flax, hemp and sisal fibers with matrices from polylactic acid and epoxy resin for aircraft wing box. Bachmann *et al.*, 2017 collected LCAs made on flax and ramie fiber and bio-based epoxy resin as a potential for aircraft components. Moreover, Gomez-Campos *et al.*, 2021 investigated natural fibers for aircraft interiors in A320neo. They compare bio composite panels made with flax fiber to conventional panels made with glass fiber. Henschel, 2019 also researched flax fiber composite for elements in a helicopter. Additionally, some papers consider hybrid composite as a viable option for aviation. These contain a mixture of natural and synthetic fiber (Arockiam *et al.*, 2018; Henschel, 2019).

When it comes to resins different types are considered in the literature. Bachmann *et al.*, 2017 said that in ECO-COMPASS project investigates bio-based thermoset resin for bio composites and claimed that the most promising are bio-epoxy and furan (PFA). However, they also say that LCAs on these are not widely covered in the literature. Further, Vidal *et al.*, 2018 presented four panels where the composites are using bio and non-bio resins. The bio-resin in their LCA is more beneficial to the environment. It is common in the literature that solely natural fiber is used while the resin is left synthetic. For instance, Gomez-Campos *et al.*, 2021 evaluated panels for aircraft interiors which have non-bio-based resin. Also, Deng *et al.*, 2014 investigated composites made from natural fibers with synthetic, such as from thermoplastic (PP) resin.

2.3.2. Opportunities and Challenges of Bio Composites

When it comes to natural fibers, they have superior properties to synthetic fibers such as low weight, low cost and biodegradability (Arockiam *et al.*, 2018). Additionally, environmental impact during production is much lower when comparing natural fibers to synthetic fibers (Duflou *et al.*, 2014). Duflou *et al.*, 2014 point out the specific advantages of flax fibers, which are the low density, wide availability, low cost, high specific properties and eco-friendly image. On the other hand, according to Arockiam *et al.*, 2018, the mechanical properties of synthetic fibers are better when comparing these to natural fibers. In particular, synthetic fibers are better when it comes to thermal stability, corrosion resistance, fatigue strength, flame resistance and moisture absorption.

The papers analysing the environmental impacts of bio composites are using LCA methodology or gathering many LCAs. For example Weiss *et al.*, 2012 combined 44 LCA studies and concludes that it is difficult to assess bio composites from an environmental perspective as in some impact categories the bio-based materials are very beneficial for the environment; however, in some not. For instance, there is a decrease in primary energy consumption and carbon dioxide emission; however, there is an increase in eutrophication and ozone depletion (Weiss *et al.*, 2012). A similar discussion is presented in Gomez-Campos *et al.*, 2021, where it is concluded that when comparing bio composite panels (flax fiber) with conventional panels (glass fiber) only climate change and marine eutrophication impact categories have a better environmental score. The other 7 investigated impact categories are better for conventional panels. However, when looking solely at carbon footprint, there is a reduction of 35% of kgCO2eq which is linked to CO2 captured by the plant (Gomez-Campos *et al.*, 2021). Another comparison of LCAs was conducted by Bachmann *et al.*, 2017 where it is summarized that replacing synthetic materials in composites can reduce the impact on the environment. Specifically, it reduces the dependence on non-renewable energy and material sources, decreases greenhouse gases (GHG) and other pollutant emissions, and enhances energy recovery and end-of-life biodegradability of components. Lastly, Duflou *et al.*, 2014 concluded that flax fiber is a good substitute from an environmental point of view for glass fiber when stiffness is a design criterion, but, not when it is strength. This is because of the lower mechanical strength of flax fiber it is necessary to use higher volume fractions of flax fibers to make the components' lifetime the same as for glass fiber composite.

When it comes to weight there is diverse information presented in the literature. For instance, Gomez-Campos *et al.*, 2021 concluded that bio-based panels are 14% heavier than conventional panels from glass fiber. It means, that any environmental advantages in production are offset by the higher fuel burn during the use phase of an aircraft. However, on the other side Vidal *et al.*, 2018 considered four different sustainable panels and all of them are lighter (even up to 31%) than conventional panels while having similar mechanical properties. Also, Henschel, 2019 concluded that by doing a tailplane in a helicopter from a hybrid composite, the saving of 4.3% in weight is possible. Le Duigou and Baley, 2014 discovered that flax fibre/polypropylene is 6% lighter than glass fiber/polypropylene composite and generates 10%-20% lower environmental burden. The majority of voices in the literature say that bio composites are lighter than conventional; however, as can be seen, not all researches agrees with that. That may be the case because of the existence of many combinations of fiber and matrix in bio composites; therefore, when looking for a final answer the very specific materials combination should be looked into.

When it comes to challenges, in papers concerning the aviation industry, one challenge is standing out, the issue of regulations. Gomez-Campos *et al.*, 2021 mentioned that the technical requirements in the aeronautics sector are stringent and that in order to achieve additional weight reduction more moderate requirements for interior fittings could be the key. The regulations concern mainly maintaining fire, smoke and toxicity (FST) standards (Arockiam *et al.*, 2018). Therefore, the factors to be verified with natural fibers are microbial resistance, fire resistance, and moisture absorption. Moreover, Henschel, 2019 concluded that the fire resistance test showed that the aviation regulations could be met with certain fluid additives. However, the regulations are still an obstacle and main challenge for the application of renewable materials in the aviation sector (Bachmann *et al.*, 2017). This is due to the safety consideration, lack of experience with these materials and confidence in long-term performance and mechanical properties of bio composites (Bachmann *et al.*, 2017).

3

METHODS

3.1. RESEARCH METHODS

The research uses qualitative and quantitative methods by conducting exploratory, transdisciplinary research where a case study on bio composites in the aviation industry is realized. Exploratory, because the complexity of the problem is not very well defined, so the nature of the issue needs to be clarified. Transdisciplinary, because it combines knowledge from innovation, environmental and economic studies. The case study is approached via ethnography since the researcher is an intrinsic part of the company - Collins Aerospace. The goal is to provide a methodology for sustainability assessment of sustainable innovation in the aviation industry which can help in the investment decision-making process. That is achieved by a combination of qualitative and quantitative research methods. Firstly, the conceptual frameworks from innovation studies are applied to qualitatively describe the potential of sustainable innovation by analysing its drivers and the development stage. Next, based on the specific case of Collins Aerospace product, quantitative methods are used for calculating the impacts of the technology on the environment (LCA), and its economic value (CBA). Such a research approach allows for in-depth investigation, and the view from different angles.

The chosen research method is a **case study** where the selected case is the bio composite technology for aircraft interiors. The reasons for choosing a case study as the research method are the following. Firstly, in order to test the sustainability assessment tools integration the process needs to be conducted on the specific example to be able to develop the methodology and conclude on the combination's challenges and opportunities. Hence, testing the integration using a specific case of technology allows for a better conclusion on the research questions. Secondly, the industry's need was to assess the sustainability of bio composite materials and their potential to be used in aircraft interiors. Therefore, to do so under the sustainability assessment framework, the creation of the case study was needed. Cousin, 2005 points out three different case study types. The one that is suitable for this research is *intrinsic case study* as it is appropriate for the study of a particular case. Here it is the bio composite technology, which will be the single case unit of analysis. The design of the single case study is presented in Table 3.1. All the phases of the research are presented with chosen data collection method and the study contribution.

Firstly, the **Literature Study** using qualitative data from other researches investigates the topic broadly on sustainability assessment and its tools, sustainable innovations, innovation analysis frameworks, and bio composites. Next, in **Bio Composite Technol-**

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Table 3.1.: Data Collection Methods

Phase of the Research	**Data Collection Method**	**Qualitative or Quantitative?**	**Research Question**	**Contribution to the Research**
Literature Study	(1) Literature	Qualitative	RQ1, RQ1.1, RQ1.3	Overview on sustainability assessment, sustainable innovation in the aviation industry, innovation theoretical frameworks, bio composites
Bio Composite Technology Analysis	(1) Literature [1], (2) Interviews [2], (3) Personal Communication, (4) Direct Observations	Qualitative	RQ1, RQ1.1	The drivers and challenges of bio composite technology in the aviation industry, the current stage of development
Decision upon bio composite material for further analysis				
The Environmental Assessment	(1) Secondary Data	Quantitative	RQ1, RQ1.2, RQ1.3	Assessment of the environmental impact of the chosen material
The Economic Assessment	(1) Primary and Secondary Data	Quantitative	RQ1, RQ1.3, RQ1.4	Comparison of costs and financial benefits from fuel costs, carbon tax, and environmental prices

[1] Journals, books, reports, thesis work, magazines and newspapers, websites
[2] Participants for interviews: (1) Collins Aerospace, (2) Bio composite companies, (3) Academic professors (12 interviewees in total)

ogy Analysis qualitative data from 12 semi-structured interviews is collected, in addition to literature, personal communications with experts and direct observations. The interviews were conducted with the company's employees, professionals in companies working on bio composites and academic professors where the list is presented in Appendix C in Table C.1. The literature where information was looked into is scientific (e.g., journals) but also website articles are used due to the fact that bio composites are an emerging topic for aircraft interiors, and the newest developments are mainly described on websites. Triangulation between all the mentioned data sources is conducted to ensure validity. These data contribute to the identification of drivers and challenges, the current stage of the technology and the material for further analysis. Next, in **The Environmental Assessment** phase the environmental secondary data from the database - Granta EduPack (2022 R1) are gathered and complemented with literature when missing. These will be collected to perform quantitative research - the comparative, fast-track LCA using the sample product for reference, the aircraft business class seat. In **The Economic Assessment** part, the primary and secondary data are used in the quantitative research. The primary, because the difference in emissions and aircraft fuel burn, is taken from the calculations in the environmental assessment part. The secondary, because the fuel prices, carbon taxes and environmental costs are taken from literature or other secondary data sources.

3.2. Case Study Protocol

Case study protocol prescribes the steps for conducting a case study. It contains instruments, procedures, and general rules. According to Yin *et al.*, 2003, the case study protocol consists of four parts: an overview of the case study, data collection procedures, protocol questions, and a tentative outline for the case study. Therefore, this subsection will be divided according to the protocol parts.

3.2.1. Overview of the case study

The case study is on one particular sustainable innovation - bio composite material for usage in aircraft interiors. The goal of the case study is to analyse the bio composite technology from environmental and economic points of view and to determine whether an investment in such innovation has the potential to bring value to the company. Additionally, the result of the case study will bring value to the academic research, conclude on the sustainability assessment process for decision-making and evaluates the integration of LCA and CBA tools.

The case study approached via ethnography research is conducted within the company - Collins Aerospace. This is because it is the project topic facilitator. In the past, the company was called BE Aerospace, and its legal name in the Netherlands is Koninklijke Fabriek Inventum B.V. Currently it is part of Raytheon Technologies. Further, in the research, it will be called Collins Aerospace. The company is one of the world's largest suppliers of aerospace and defence products. They, inter alia, produce products that are used in aircraft interiors, such as seats, ovens, or microwaves. When it comes to sustainability, Collins Aerospace actively participates in pursuing green aviation. In 2019, the company joined the leaders in aerospace and signed the Clean Sky 2 Joint Declaration of European Aviation Research Stakeholders to lead the way toward the decarbonization of aviation by 2050. Additionally, in 2021, they signed the Air Transportation Action Group's declaration to Fly Net Zero by 2050 (Aerospace, n.d.). Since the company is showing extraordinary interest in sustainability, this makes the company a great organization to do this ethnography research.

3.2.2. Data collection procedures

The data collection methods for each phase of the case study are as presented in Table 3.1. In order to do the interviews with Collins Aerospace employees, access to this company is essential. Therefore, it was crucial that the Master Thesis author was employed on an internship basis, as it enabled access to many industry experts. Additionally, professionals from companies developing bio composites were more enthusiastic to talk with a person from a big aviation company. All the research participants were informed about the author's relation with Collins Aerospace and the purpose of data collection, also were asked to sign the consent form presented in Appendix C on Figure C.1.

When it comes to data protection, the Data Management Plan (DMP) was created. In summary, the most important information from DMP is the following. All the interview data were stored by the Master Thesis author on TU Delft OneDrive, and only the TU Delft research team had access to it. In order to have more reliable responses it is a good practice to keep employees' responses separated from the company. The company supervisor; however, had access to summaries from interviews. In the Master Thesis, no personal data of participants is indicated, only the general profession of the employee or professor is mentioned to prove the person's relevance to the topic. To prevent participants' re-identification the country where the person is working is not indicated, and since Collins Aerospace has 68,000 employees in the whole world, this risk was mitigated. All the data from interviews will be kept up to 2 years after the Master Thesis publication for future research purposes. When it comes to sensitive data from the company, in the final Master Thesis only the necessary information is published keeping the names of the products only very general. In particular, no product-specific name is mentioned, only the general name like a business class aircraft seat. The data that can be published was constantly discussed with the company supervisor during the research duration. Lastly, the technical data was kept solely on the Collins Aerospace laptop with restricted access to the Master Thesis author and company supervisor.

3

3.2.3. PROTOCOL QUESTIONS

Protocol questions are the ones that the researcher poses to themself, accompanied by sources of evidence where the answers are supposed to be found. The protocol questions are not presented in this paper; however, these questions were asked, and the answers are presented in the column of 'Contribution to the Research' of Table 3.1.

3.2.4. TENTATIVE OUTLINE FOR THE CASE STUDY

The last section of the case study protocol is consisting of the likely audience, format of data, and use of data. In the case of this research, the audience which is going to look at the case study results is the graduation committee, Collins Aerospace company, and interested professors, students or the public. The final output in which the data will be shown is this Master Thesis which will be publicly available in the TU Delft repository. Due to the audience, the results should be useful for the company but also consider an academic approach and be repeatable for future research. Moreover, the data format was gathered in Excel files, where the results from interviews and the analyses were developed. Additionally, the fast-track, comparative LCA and CBA calculations, including fuel savings and materials costs, were also carried out using Excel.

3.3. THEORETICAL BACKGROUND OF LCA AND CBA

The Master Thesis integrates two tools to conduct a sustainability assessment and to answer the research question. For environmental impacts assessment, it is Life Cycle Assessment (LCA), and for comparison of environmental impacts and financial costs, it is Cost-Benefit Analysis (CBA). These two and the theory behind them are explained in the sections below.

3.3.1. LIFE CYCLE ASSESSMENT

Life Cycle Assessment (LCA) is a process to calculate the effects of processes, products, and services on our planet (Akhshik *et al.*, 2017). The methodology is defined by ISO standards 1404X and is divided into four stages as the following (Guine *et al.*, 2002).

1. **Goal and Scope Definition**
   - describing system boundaries and functional unit,
   - specifying the objective of the study,
   - acknowledging study limitations,
   - identifying the audience.
2. **Inventory Analysis**
   - collecting input and output data,
   - quantifying material use, energy use, environmental discharges and associated waste with every life cycle stage.

3. **Impact Assessment**
   - translating raw data into the potential impact on the environment and human health,
   - using impact categories, category indicators, characterization models and weighting values.
4. **Interpretation**
   - takes place through all the three previous stages (iterative process),
   - assessing the results in the context of the study goal.

The commonly used LCA definitions are explained. The **functional unit** "defines and quantifies the identified functions and should be consistent with the goal and scope of the study. Typically, the functional unit includes an identification of the product, an amount of the function, a time value and a quality value" (Guine *et al.*, 2002). The **system boundaries** present the scope of LCA, are determined by the study's objective and the typical distinction is as follows (Guine *et al.*, 2002):

- Cradle-to-Gate - from raw material extraction to factory gate,
- Cradle-to-Grave - from raw material extraction through product use and disposal,
- Gate-to-Gate - from one defined point along the life cycle,
- Cradle-to-Cradle - to indicate that it is a cradle-to-grave study where the product is recycled in the end.

The **impact categories** are the LCA metrics that allow grouping different emissions into one effect on the environment. The most commonly used are (Guine *et al.*, 2002): Greenhouse Warming Potential (also referred to as Carbon Footprint), Ozone Depletion Potential, Acidification Potential, Eutrophication Potential, Consumptive Water Footprint and Water Emissions Footprint, Eco and Human Toxicity Assessment, Direct land Use, or Water Use. However, there is more and which impact categories are chosen depends on the used method.

Lastly, LCA can be used to support decision-making by assessing the impact on the environment of the future product. It can also serve for comparison purposes of two systems that deliver the same product/service. Additionally, it can help the companies to provide environmental claims on their products (Guine *et al.*, 2002).

3.3.2. COST-BENEFIT ANALYSIS

The Cost-Benefit Analysis (CBA) is the process of comparing the estimated or projected costs and benefits in order to determine whether it makes sense from a business perspective. It involves tallying up the project's costs and subtracting that amount from the total projected benefits (Stobierski, 2019). Logically speaking, when the benefits exceed costs the project or the decision is a good one to make. The CBA is a data-driven approach; therefore, it is less prone to biases. However, some variables, especially indirect and intangible costs might be hard to assess. Hence, incorrect data might change the analysis results (Stobierski, 2019). According to Stobierski, 2019, the stages of CBA are following:

1. **Establish a Framework for Your Analysis**
   - identification of goals and objectives of the analysis,
   - decision upon the used metrics for the comparison of benefits and costs.
2. **Identify Your Costs and Benefits**
   - compiling two separate lists of costs and benefits,

    - recognizing direct, indirect, intangible costs and benefits,
3. **Assign a Dollar Amount or Value to Each Cost and Benefit**
    - establishing the common monetary unit.
4. **Tally the Total Value of Benefits and Costs and Compare**
    - comparing monetary values.

The important definitions in CBA are the following (Stobierski, 2019). The **direct costs** are the expenses that are related to the development and production costs of the product or to the implementation of the product. The **indirect costs** are typically the expenses that are fixed such as rent, that contribute to the business operation. The **intangible costs** are the most difficult costs to quantify. For instance, these are the costs of losing customer satisfaction because of releasing a new product. The **direct benefits** relate to the increased revenues or sales. The **indirect benefits** describe for example the improved customer interest in the company. Lastly, the **intangible benefits** refer for example to improved morale of the employees.

3.4. Research Flow

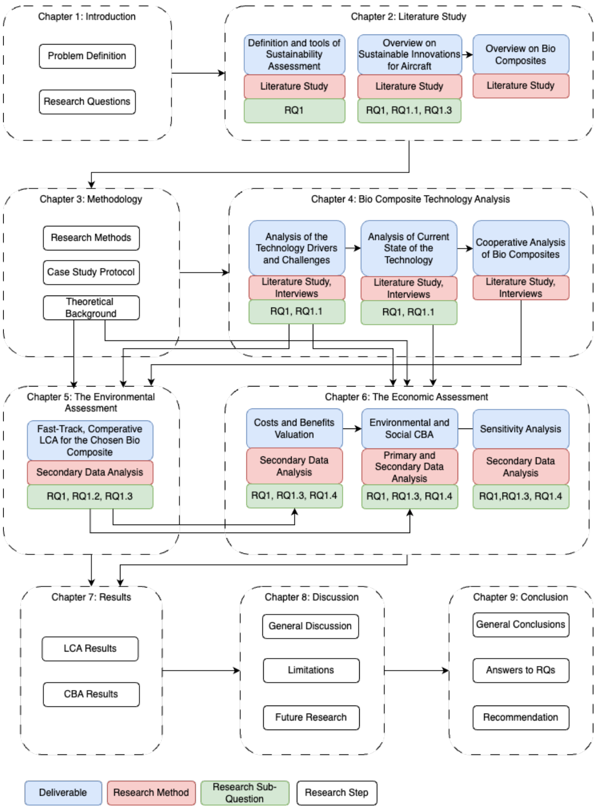


Figure 3.1.: Research steps

4

Bio Composite Innovation Analysis

The purpose of the analysis is to understand the drivers, bottlenecks, current state of bio composite technology and the bio composites variations. In order to do so, the theoretical frameworks from innovation studies were used instead of regular market analysis which is a business practice. It starts with the theory of composite technology, which is essential for further topic understanding. Then the recognition of drivers for bio composite materials development is determined using a theoretical approach. Next, the challenges are pointed out. Following that, the analysis of the innovation development stage is conducted where the technology pattern is recognized for the bio composite materials in the automotive and aviation industry. In addition, the analysis of the development stage of bio composites in Collins Aerospace specifically is determined. Lastly, the comparative analysis of different material composition in bio composites is presented where currently produced materials are investigated. The conclusion of this chapter is the decision on bio composite for further analysis in the following parts of this thesis.

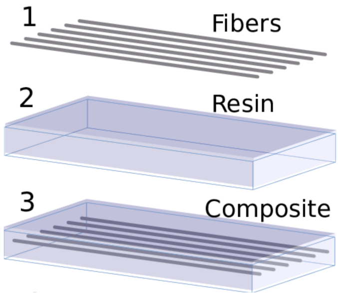
The bio composite technology was chosen because of the recognized knowledge gap and the Collins Aerospace company's interest in that topic. The knowledge gap occurs because the research on the environmental benefits of bio composites for usage in aircraft interiors is minimal. Moreover, there is no detailed economic assessment available. Nevertheless, the potential is recognized by the literature and experts, which needs to be validated. Hence, further research on that subject is justified.

Since the topic is not that widely investigated in the literature the experts' knowledge is very valuable for the analysis. Hence, the interviews, personal communications and direct observations served for filling in the missing gaps, for resolving contradictory information presented in the literature and for sensing the approach in the aviation industry towards bio composite materials.

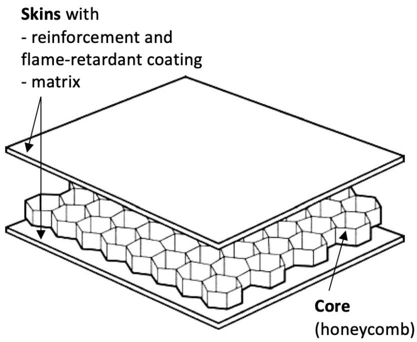
4.1. Theory of Bio Composite Materials

To understand what is bio composites it is important to understand what composite material is. Arockiam *et al.*, 2018; Sathishkumar *et al.*, 2014 describe composites as materials that consist of more than one chemically distinct constituent. In other words, one composite material can consist of many sub-materials and when combined give better properties than each of them individually. Additionally, the sub-materials do not lose their individual identities. The focus of this thesis is on fiber-reinforced composite materials, which are obtained by embedding *fibers* which are stronger and stiffer; therefore, 4

are *reinforcement* into a *matrix* which is softer and weaker, usually the *polymer resin* (Beer *et al.*, 1992). The layers of the large number of parallel fibers embedded in the matrix create *laminate* structure also called a composite plate (Beer *et al.*, 1992). One such layer is presented in Figure 4.1a. There are also special class composites which have a structure called *sandwich*. The name stems from the fact that the *core* of this structure is between two laminates, which are called *skins*. Moreover, in such sandwich-structured composites, the core is usually a *honeycomb* where the name stems from its geometry (Ramnath *et al.*, 2019). The honeycomb composite is presented in Figure 4.1b. Lastly, the further used term *composite panel* is the flat composite structure which in the case of aviation panels has usually a honeycomb form.



(a) Sub-materials of one layer of composite material. Source: Jareteg *et al.*, 2016



(b) Honeycomb composite material

Figure 4.1.: Constituents and structure of composite materials

Bio composites are composites where either fiber is natural or resin is bio-based or both. Hence, in the literature material is called bio composite also when consists of natural fiber but polymer (plastic) resin. To sum up, when considering bio composites, both fiber and resin need to be specified. Additionally, when sandwich or honeycomb structure is analysed, also the material of the core and skins need to be indicated separately.

4.2. TECHNOLOGY DRIVERS

To identify the factors affecting the adoption of the technology the literature stream was used - *institutional theory*. Out of the theoretical approaches to innovation presented in the literature study in chapter 2, this one was chosen because of identified pressures from outside actors which are influencing the development of bio composites in the aviation industry. In particular, the pressures are from regulatory institutions, customers, competitors and intrinsic motivation; hence these were classified and discussed using the institutional theory, which divides the drivers into three types of pressures: coercive, mimetic and normative (DiMaggio & Powell, 1983; Latif *et al.*, 2020). Lastly, DiMaggio and Powell, 1983 argues that these pressures are not always empirically distinct and may intermingle.

4.2.1. COERCIVE PRESSURES

According to DiMaggio and Powell, 1983; Latif *et al.*, 2020, coercive pressure is applied by government authorities or non-governmental organizations which forces organizations to comply with regulations or standards. That driver is highly visible in the aviation industry as many initiatives and incoming regulations are aiming to reduce emissions from the aviation industry. For example, 28 EU Member States, included all the flight emissions which are to, from and within the EU starting from 2012 in the EU Emissions Trading System (EU ETC). They set a cap which says that by 2030 the total amount of certain greenhouse gases that can be emitted should be 43% lower than that in 2005 (Bachmann *et al.*, 2017). In 2021 it was revised and EU, 2021 published that the goal is to achieve net emissions reduction of at least 55% in 2030 when comparing it to 1990 levels. Additionally, Gomez-Campos *et al.*, 2021 mentions that European Commission, through the Advisory Council for Aviation Research and Innovation in Europe (ACARE), set the goals for 2050 to reduce 75% of CO2 and 90% NOx emissions per passenger kilometre. In addition, the goal is also to make aircraft recyclable (de Investigación & de TransportesComisión Europea. Dirección General de Investigación, 2011). Currently, the Net Zero Emission 2050 is influencing the decisions within the aviation sector, which can be seen by work on GHG emissions from Scope 1, 2 and 3 which is currently happening in Collins Aerospace and other aerospace companies (direct observation, 8 March 2023). According to an expert in transport policies, within 10 years in the EU there will be environmental requirements and standards for any products; therefore, so-called 'Eco labels' might be an obligation on all the products for aircraft (Interviewee 11). Moreover, the carbon tax, which charges airlines for their emissions is already implemented in Europe and is predicted to grow (Collins Aerospace employee, personal communication, 9 May 2023). That is also confirmed by the Kornbakk, 2022 article. Lastly, Interviewee 11 stated that ICAO is a responsible party in the aviation sector for Paris Agreement; however, since it combines 180 countries this makes it difficult to implement any regulations (Interviewee 11). Therefore, he/she predicts that the EU will be the first one to introduce stricter regulations on emissions reduction. Such policies will affect ticket prices, in turn, airlines and airports, and finally the whole aviation industry.

4.2.2. NORMATIVE PRESSURES

According to DiMaggio and Powell, 1983; Latif *et al.*, 2020, normative pressure emerges from values, expectations, and standards within an organization's culture. In other words, it is a pressure stemming from inherent motivation where a company believes that a decision is the right thing to do. That driver influences the sense of responsibility and norms (Latif *et al.*, 2020). According to the Collins Aerospace employee, sustainable innovation and in particular sustainable materials are developments that are the "right things to do" (Interviewee 9). Also, another employee said that fossil fuels may not be possible to be used forever; hence, the company needs to find a way to replace them (Interviewee 10). Moreover, the company is already investing in sustainable materials which are in detail described in section 4.4.2. Therefore, the sense of responsibility is visible in Collins Aerospace company. Additionally, other aviation companies also feel the duty to change towards sustainability. For instance, Airbus, a customer of Collins Aerospace, started demanding an indication of the environmental impacts of products as they want to introduce the 'Eco-efficiency labels' in their catalogues (direct observation, 9 May 2023). Moreover, customers are also requesting recyclable products and the Life Cycle Assessment of these (direct observation, 9 May 2023). Thus, currently, the customer demand for sustainable solutions is visible. In addition, society is pressing either which is mentioned by the literature and experts (Interviewees 4, 11, Flaherty and Holmes, 2020; Gunziger *et al.*, 2022; Santos *et al.*, 2016). For instance, flight shaming is recognized as a trend where air travel is socially unacceptable because of the negative impact of flying on the environment (Flaherty & Holmes, 2020; Gunziger *et al.*, 2022).

The way bio composite technology responds to the normative pressures is the fact that implementing these in aircraft interiors has **environmental reasons**. These materials have a lower impact on the ecosystem during manufacturing and end-of-life stages than synthetic composites (Joshi *et al.*, 2004). For instance, natural fibers are claimed to reduce dependence on non-renewable material sources and enhance energy recovery with end-of-life biodegradability of components (Joshi *et al.*, 2004). Therefore, according to the expert in bio composite technology for bridges, the reason for implementing bio composite is that it is a "circular and sustainable solution" (Interviewee 1).

4.2.3. Mimetic Pressures

According to DiMaggio and Powell, 1983; Latif *et al.*, 2020, mimetic pressure stems from the fact that companies follow their competitors when seeking superior performance. In the case of bio composites, Collins Aerospace's competitors are developing products which are using bio-resins. For instance, company Pitch Aircraft Seating Systems used bio-resins to develop lightweight economy class seats weighing around 7kg each (Gavine, 2020). Additionally, competitors are focusing on significant weight reduction. For example, Expliseat produced seats from titanium and composites (but not bio composites) which are 4kg, when on the contrary seats of different companies are around 10-15kg (Business Insider, 2014). Therefore, the trends in the industry are visible, and mimetic pressure drives aviation companies to produce lighter and more sustainable products for aircraft interiors. Due to the mimetic pressures and the customer's demand for sustainable solutions, companies such as Collins Aerospace should respond, where bio composites might be one of the answers, as the business opportunity is recognized here. According to the employee of Collins Aerospace, having products from bio composite materials would be good for marketing purposes (Interviewee 12). Additionally, he/she believes that airlines would be willing to pay even more for such a product. Moreover, he/she said that: "I do think that the demand is there". Developing the technology may have economic benefits for both Collins Aerospace and its customers. In addition to that, the aviation industry is imitating the automotive industry. According to the academic expert, aviation is not a leader in sustainability; therefore, the drive comes from other industries (Interviewee 6). Interviewee 9, the Collins Aerospace material expert, confirms that by saying that the global market starts discussing bio composites in other industries, especially in automotive. This is supported in the literature by Walls, 2022 which says that sustainable technology developments for aviation are influenced by other industries such as automotive.

The reason why producing lightweight products is so important is because of the **economic reason** which relates mostly to the potential of lower fuel burn, and consequently, lower operational costs for airlines. Therefore, as said by the academic expert "the major driver is weight saving" (Interviewee 4), and an industry expert from Lufthansa Technik AG confirmed it adding that bio composites give a possibility to save weight (Interviewee 3). Interviewee 8 from Bcomp company which is producing flax fibers for bio composites said that in the case of these materials, sustainability and cost efficiency are linked together. Bio composites that are lighter than conventional materials do save both operational emissions and costs. The second one is especially important for airlines as fuel represents ca. 25% of operating expenses for the global air transport industry (Gomez-Campos *et al.*, 2021). This number is considered even bigger among Collins Aerospace employees, as between 30-50% (Collins Aerospace employee, personal communication, 9 May 20223). Additionally, according to the interview with Bruno Dellier, the EcoTechnilin R&D engineer, it is predicted that the price of bio composites will be similar to glass/epoxy composite currently used in aircraft interiors (Black, 2015). Experts from companies producing bio composites for aviation (EcoTechnilin and Lufthansa Technik) said both that their materials are still more expensive than conventional composites from glass fiber; however, they predict lowering the price when scaling up (Interviewees 2 and 3). In particular, EcoTechnilin's material is currently 3-4 times more expensive than conventional composite (Interviewee 2). When it comes to information from Collins Aerospace employees, they claimed the cost-effectiveness of bio composites is not fully known yet (Interviewees 7, 9 and 10). They said that this is something that still needs to be found out.

To sum up, aviation companies are pressured by institutions to develop sustainable innovations. The literature and industry experts claim bio composites are a sustainable solution; however, the recognized gap is in the very little number of environmental assessments of these materials specifically for aircraft interior purposes. Therefore, validation of environmental benefits for the usage of bio composites in aircraft interiors needs to be further conducted which will be done in chapter 5. Additionally, economic benefits from bio composites usage are also predicted because these have the potential to be lighter. However, the information from experts and within the literature is not fully consistent on whether the fuel cost saving would be high enough to cover the higher costs of bio composites. Therefore, in chapter 6, economic benefits will be assessed using specific examples to prove or reject the financial potential of the technology.

4.3. TECHNOLOGY CHALLENGES

The technology of bio composite materials is promising; however, to have a full overview the challenges need to be also recognized. The recognized problems from literature and interviews are discussed further.

The biggest challenge with natural fibers that was mentioned is the **lack of consistency** in final mechanical properties (Interviewees 7, 9, 10 and 12). This stems from the fact that the properties might vary from season to season and between places of growth. Therefore, unless the flax production is controlled very well to ensure repeatability, a product that uses bio composite with natural fiber might have a problem passing the aviation certification tests. Surprisingly, this issue did not stand out during the literature study; however, was pointed out during interviews. Therefore, to confirm that the literature was looked into again and supported the interviewees' opinion. For instance, Bachmann *et al.*, 2017 said that "lack of experience and confidence in the long-term performance and mechanical properties of composites made of renewable materials is still an obstacle for their usage". Additionally, the paper of Pillin *et al.*, 2011 which investigates the mechanical properties of flax fiber in the 4-year study also confirms that issue. The research concludes that meteorological conditions during flax growth have a strong impact on the quality of fiber. On the other side, the research of Lefeuvre *et al.*, 2013 investigated eight flax samples from three different years and various climate conditions and showed that all the samples could compete with glass fiber properties. However, the literature does not say how difficult it is to overcome this challenge.

Another obstacle that was mentioned by industry and academic experts is the fact that **natural fibers are flammable** which might cause problems in passing certification tests (Interviewees 3, 6, 7, 8, 10 and 12). That issue was highly recognized in the literature either. Santos *et al.*, 2016 mentioned that bio composites are promising materials; however, need validation in regards to flammability. Arockiam *et al.*, 2018 say that it is necessary to coat flax fiber before incorporation with the matrix. This is because its fire resistance is moderate. However, that challenge was managed to be overcome by a few projects and companies which will be discussed in section 4.4.1. For instance, Arockiam *et al.*, 2018 used the statement of Pedro Martin, the material scientist in Boeing Research and Technology Europe, that to overcome this challenge flax fibers should be treated with halogen-free flame retardant.

To sum up, the mentioned here challenges were repeated by interviewees and literature. The challenge of flammability was managed to be resolved by a few organizations (section 4.4.1). However, the problem with reproducibility seems to be still a technology bottleneck. The analysis of the challenges shows that the technology is immature due to consistency problems. Also, it is predicted that the suitable material for further analysis from an environmental and economic point of view should be done on the specific material that already passed the flammability requirements for aircraft interiors. However, to determine how mature is the technology and which material would be suitable for aircraft interiors further analysis on bio composites needs to be done.

4.4. Innovation Development Stage Analysis

The pattern of technology innovation presented in this section is analysed first with a focus on the automotive industry, and then on the aviation market. The reason for that is the fact that these patterns were found to be significantly different. Therefore, in order to show the scale of discrepancy in the technology development the two patterns are presented. Next, the projects on bio composites within Collins Aerospace are presented. Finally, the information from the pattern of technology innovation is used to make the conclusion on the reason behind such a discrepancy between the two industries. As determined in the section 2.2.2, the innovation can be analysed on different levels. The relevant levels for that research are the project and pattern levels. The bio composite innovation is analysed by looking at the academic frameworks of both levels. Since the project level is discussed within the organization boundaries, first the pattern of the technology will be analysed to determine the stage at which the technology is between the organizations.

4.4.1. Pattern Level Analysis

The model of technology innovation pattern is analysed based on **Evolutionary Model** of Ortt *et al.*, 2010. It is an extended model of the S-curve of Rogers, 1965 which is also called Life Cycle Model.

Bio composites in the automotive industry

Innovation Phase
According to Baley *et al.*, 2021, in the 1930s the bio composite such as cotton fabric impregnated by phenolic resin was used for the design of mechanical parts such as gears (Gordon, 1994). The material found its application in marine transmission components or later in bomber plane production when the aluminium alloy was short in supply (Baley *et al.*, 2021). However, it had mechanical problems. To learn more about the material, in 1937 De Bruyne published his work when he investigated cotton-reinforced phenolic composites (de Bruyne, 1937). Later, in 1939 he proposed another bio composite consisting of flax fiber and phenolic resin (De Bruyne, 1939). Consequently, he became a pioneer in the area of plant fibre composites (Baley *et al.*, 2021). Because the study of De Bruyne in 1937 covered many problems of bio composites that work can be indicated as an **invention** of the technology. This date is chosen also by Baley *et al.*, 2021 as the starting date of bio composite innovations.

Adaptation Phase
The end of the innovation phase and the beginning of the adaptation phase is when the initial market introduction takes place. According to Baley *et al.*, 2021 the use of plant fibers to reinforce polymers for aircraft parts started in 1939. However, the paper is not stating any of these applications and it is hard to track them. Therefore, a different event which occurred in 1941 is identified as **initial market introduction**. Henry Ford presented a car where body panels were made from fiber-reinforced soy-protein plastic (Baley *et al.*, 2021; Błędzki *et al.*, 2012). Elseify *et al.*, 2021 states that the mass production of such cars was not economical back then. Therefore, it is recognized to be only an initial market introduction, not a mass production.

Market Stabilization Phase
The end of the adaptation phase and the start of the market stabilization phase is indicated by the milestone of **industrial production**. In the case of bio composites, it is the production of Trabant which started in 1958 (Baley *et al.*, 2021). The car had components made from thermosetting phenolic resin reinforced with natural fibers of cotton (Baley *et al.*, 2021; Sonntag & Barthel, 2002). The production of Trabant lasted till 1990 (Elseify *et al.*, 2021). Following that more and more car manufacturers started using bio-based materials including General Motors (in Chrysler), Mazda, Mitsubishi, Toyota and Ford (Allen, 2018; Barrett, 2019). Additionally, the technology started to be used in Formula 1 cars. For instance, McLaren with Bcomp developed seats for the F1 car (in Textiles United Kingdom Transport/Aerospace, 2020). Also, Super Formula, Japan's top-line single-seater series, will have new bodywork made from Bcomp's bio composite (Efinger, 2022; Wood, 2022). According to the expert working with bio composites, the car industry has been using bio composite for quite some time in big amounts (Interviewee 1). Also, the industry expert confirms that by stating that EcoTechnilin company is producing bio composites for the automotive industry since 2001 and the market is growing every year (Interviewee 2).

The summary of the technology pattern described above is presented in Figure 4.2.

Bio Composites in Commercial Aviation

Bio composite materials in aviation have been tried to be implemented from the very beginning; however, according to industry experts there is no bio composite application

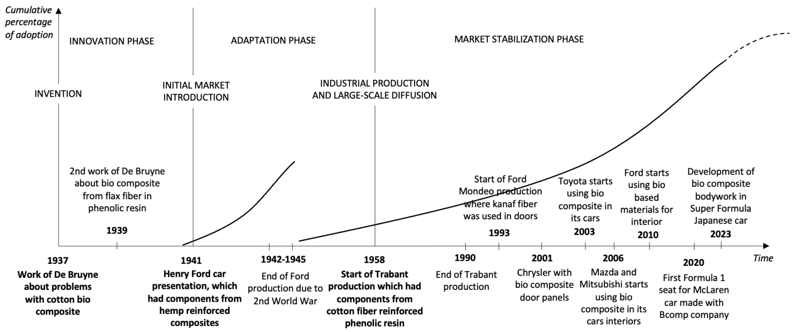


Figure 4.2.: Pattern of bio composite technology development in the automotive industry. Own elaboration based on Evolutionary Model of Ortt *et al.*, 2010.

in current airliner aircraft (Interviewees 2, 3 and 8). Therefore, in commercial aviation, it is still an emerging topic. Currently, the main players in that area are **EcoTechnilin, Bcomp and Lufthansa Technik**. These companies are developing advanced bio composites for mainly sport and automotive industries; however, also tried to enter the aviation market. EcoTechnilin produced material **FlaxPreg T-UD FR** and Lufthansa Technik produced **AeroFLAX** in a partnership with Bcomp which is responsible for ampliTex™ and powerRibs™ flax fiber reinforcements used in AeroFLAX. According to the industry professional from EcoTechnilin, the aviation industry was not interested in natural fiber composites until very recently (Interviewee 2). The professional from Lufthansa Technik confirmed that by mentioning that they started developing bio composite - AeroFLAX - in 2017; however, there was no demand for their product (Interviewee 3). It is also worth mentioning that EcoTechnilin's product FlaxPreg T-UD FR and Lufthansa Technik's material AeroFLAX both meet the requirements of flammability; however, are not officially certified as it requires a confirmed client. The industry expert from Bcomb said that their material, which is the reinforcement used in AeroFLAX, passed the flammability tests and is ready to be used in commercial aircraft. Now the company is in the final stage of finding the best balance between mechanical properties and fire resistance (Interviewee 8). Additionally, he/she said that currently there is an interest in the material, especially from aircraft OEMs which is bigger than interest from airlines.

In addition to these, a few interesting projects and collaborations were created and are working on bio composites for aircraft interiors. All the projects are gathered in Table 4.1. The timeline of these projects is presented in Figure 4.3, where the numbers in the figure correspond to the numbers from Table 4.1. Figure 4.3 also contains information from interviews which are the prognosis of bio composite future in the aviation industry.

4.4.2. Project Level Analysis

A project level analysis is based mainly on the interviews with the Collins Aerospace employees. These are Interviewees 7, 9, 10 and 12. According to Interviewee 7, Collins Aerospace participated in one EU project - SuCoHS between 2018 and 2022 where detailed LCA analysis on using PFA bio-resin was developed. To explain, according to In-

Table 4.1.: Most significant projects and partnerships for bio composite developments for aircraft interiors

Nr	Partnership	Description	Type of project
1	Airbus & South African CSIR, (News, 2008)	(1) work on natural fibers (hemp, flax, and kenaf); (2) focus on sidewall and ceiling panels	Research and development
2	Bcomp with Airbus investment, (Wire, 2022)	(1) work on natural fiber composites	Research and development
3	Cayley project (Boeing Research and Technology Europe, Invent GmbH, Aimplas and EcoTechnilin), (Black, 2015)	(1) panels using skins from "FlaxTape" fiber of EcoTechnilin and matrix from renewable polymers; (2) four novel panels meeting the mechanical properties; (3) 35% lighter than glass fiber composite,	Material prototype - **partially bio-based** composite, meets the flammability requirements (FAR 25.853)
4	EcoTechnilin, (Pasion, 2021), (interviewee 2)	(1) developed material "FlaxPreg T-UD FR" using the "FlaxTape" reinforcement; (2) 50% flax fiber and 50% epoxy resin; (3) developed in 2014 but no demand from the client yet	Material prototype - **partially bio-based** composite, meets the flammability requirements (FAR 25.853)
5	ECO-COMPASS (Europe & China partnership), (Bachmann *et al.*, 2018; Kostov, 2018)	(1) aims to develop and assess ecologically improved composites for the aviation; (2) part of Horizon 2020 research	Research and development
6	Lufthansa Technik & Bcomp, (Dubois, 2022; Nehls, 2022)	(1) developed material "AeroFLAX" from flax fiber and PFA resin (agricultural waste); (2) claimed to save 20% including redesigning a component (Interviewee 3)	Material prototype - **fully bio-based** composite, meets the flammability requirements (FAR 25.853)

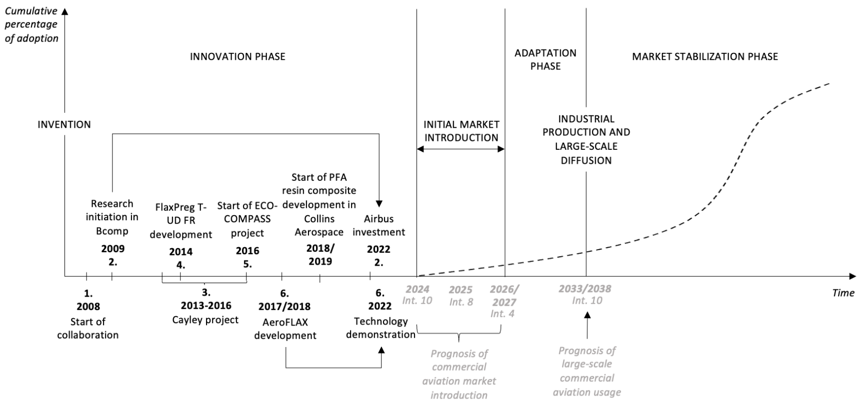


Figure 4.3.: Timeline and prognosis of developments in bio composites in the aviation industry. Own elaboration based on Evolutionary Model of Ortt *et al.*, 2010.

terviewee 10, PFA thermoset resin is made from sugarcane industry waste; therefore, it is a bio-based resin; however, not biodegradable. In addition to that, he/she mentioned three other internal projects concerning bio composites. Moreover, Interviewee 7 concluded that currently more work is done on the development of materials with bio-resin and less focus is given to natural fibers. Interviewees 9, 10 and 12 confirmed the fact that the biggest focus is on bio-resins, especially PFA resin. According to Interviewee 9, the project on composites with PFA resins started more than 5 years ago in Collins Aerospace; however, Interviewee 10 said that the company works on it for the past 3,5 years. Both Interviewees 9 and 10 mentioned that the focus is on resins since it is a more mature technology and it is closer to meeting requirements. While for fiber the obstacles are concerning problems with repeatability mentioned in section 4.3. In addition, Collins Aerospace is working on replacing metallic structures with lightweight composites; therefore, research in that area is very much in place. To determine the stage of bio composite development within Collins Aerospace company, the stage-gate approach is used presented in Figure 4.4. It can be assumed that bio composite technology is on STAGE 2: Build the Business Case, where more detailed market and technical research is conducted. This is because the company is already researching for quite a time and the most viable option are already selected. Even though most of the focus is on bio-resin, not bio-fiber, the first steps towards bio composites are taken and building a business case from that has started.

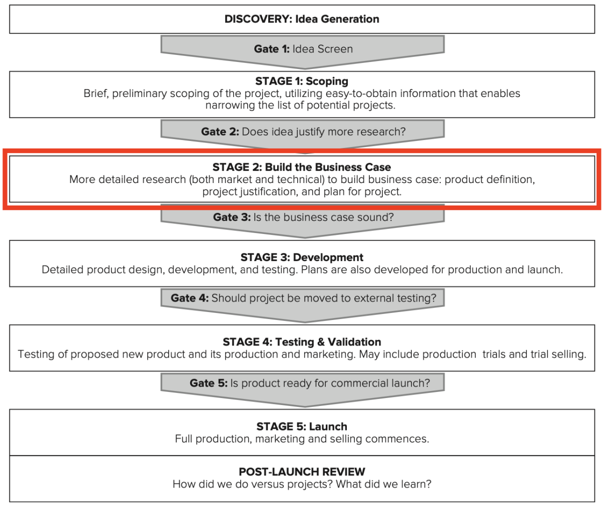


Figure 4.4.: Bio-composite development on project level based on the stage-gate framework of Cooper, 1990. Own elaboration based on figure in Schilling, 2020.

Looking at the results from this section, the following conclusions can be made. First, the bio composite materials are widely used in the automotive industry; however, in the aviation industry, it is still an emerging topic. In particular, only three players were found that developed a bio composite that meets the aviation requirements. The materials are not used in commercial aviation yet; however, the experts' prognosis is that in 1-4 years these will be implemented. That insight is further used in determining the time frame for the economic assessment in chapter 6. Moreover, Collins Aerospace itself is very much interested in sustainable materials; however, natural fibers are not considered yet by them. Hence, the question is why such a difference in the development stage between the aviation and automotive industry exists. The answer might be in the very strict requirements for the aviation industry and the fact that to introduce new products for aircraft interiors a set of very expensive certification tests need to be developed. That results in a slower pace of industry innovativeness. However, as concluded here, such materials exist which are predicted to pass the certification tests; therefore, further analysis to compare the materials that can be used in aircraft interiors and to determine the most suitable ones need to be developed.

4.5. Comparative Analysis of Bio Composites

As discussed before in the section 4.1, bio composite can be both natural fiber-reinforced plastic resin and natural fiber-reinforced bio-based resin. The first one is researched more often within the available literature (Deng *et al.*, 2014; Joshi *et al.*, 2004; Le Duigou & Baley, 2014; Shen & Patel, 2008); however, there are papers investigating the fully bio-based composite either (La Rosa *et al.*, 2014). The decision on the bio composite for further analysis is made based on three categories: environmental impacts, material costs and recyclability. These will be analysed in the following subsections.

4.5.1. Environmental Impacts

The environmental data were gathered during the literature study and chosen impacts, such as carbon footprint, energy consumption and water usage were collected. The found approaches to LCA were the following. Either the research was focused solely on fiber and conducted cradle-to-gate environmental analysis (from raw material to the customer), or the whole composite was assessed including fiber and resin production with composite manufacturing impacts. Moreover, the chosen fibers for analysis are the fibers mentioned most often in the literature as viable materials for bio composite. These are flax, hemp, jute, and kenaf fiber. On the contrary, the resins in the context of bio composites are investigated less often in the literature; therefore, the most probable solutions were chosen from the interviewees' responses. These were: bio-resin (Interviewee 1), epoxy (Interviewee 2, used by EcoTechnilin), PFA from waste products of the sugarcane industry (Interviewee 3, used by Lufthansa Technik; Interviewees 7, 9, and 10, considered by Collins Aerospace), and PEI or phenolic resin (Interviewee 6, because of good flammability resistance). As can be seen, not all of these resins are bio-sourced.

The environmental impact varies between researchers, which stems from the fact that each LCA includes and excludes different steps of production, the production place is assumed to be in a different place, or transportation routes differ. This process discovered that each study is taking into account different assumptions; therefore, the results are significantly different. For instance, for flax fiber the carbon footprint in kgCO2eq varies from 0,8 in Barth and Carus, 2015 to 0,3 in Le Duigou *et al.*, 2011, even though all the researches were cradle-to-gate studies. For hemp fiber the difference in energy consumption varies from 5,00 in Barth and Carus, 2015 to 13,2 in Gonzlez-Garca *et al.*, 2010. Hence, it was difficult to choose the proper for this research number. Therefore, in this thesis to have a more reliable overview of the environmental impacts of constituents of bio composite material the data was gathered from one database - Granta EduPack (2022 R1). Using one source is advantageous as the assumptions for all the considered materials are equal. The environmental impacts for the mentioned materials from Granta Edu-

Pack are presented in Table 4.2. All the detailed environmental impacts gathered from the literature study and from databases are shown in Appendix D in Table D.2, where averages collected together are presented in Appendix D in Table D.1.

Table 4.2.: Environmental impacts per 1 kg of produced material, from Granta EduPack database, for materials that are most commonly used in bio composites

Investigated Material	Carbon Footprint [kgCO2eq]	Energy Consumption [MJ]	Water Usage [l]
FIBER			
Flax Fiber	0,44	11	3300
Hemp Fiber	1,6	9,99	2600
Jute Fiber	1,05	104	2380
Kenaf Fiber	1,35	174	1500
MATRIX (RESIN)			
Bio-epoxy Resin [1]	4,08	1,9	-
Epoxy Resin [2]	6,97	92,25	-
PFA Resin (Furan)	2,1	-	-
Phenolic Resin	1,96	80,5	54,4
CORE (WHEN SANDWICH STRUCTURE)			
PEI Foam	19,9	145	541

[1] No data in Granta EduPack database. Data were taken from literature La Rosa *et al.*, 2014.
[2] No data in Granta EduPack database. Data were taken from literature Bachmann *et al.*, 2017.

From the analysis in the literature, it can be concluded that flax fiber for replacement of glass fiber is mostly discussed (evidence in Table D.1). That observation was compared to the information delivered from interviews. All the interviewees mentioned flax fiber as a suitable material, additionally, the two available on the market bio composites for aviation are also using flax fiber. Moreover, interviewee 8 from Bcomp says that flax fiber has the most reliable supply chain, is efficient, financially achievable and has good mechanical properties. Additionally, according to the Granta EduPack database, it can be seen that the carbon footprint of flax fiber is the lowest (Table 4.2). Besides this, bamboo fiber was also mentioned by two academic experts on bio materials (Interviewees 4 and 6); however, according to Interviewee 6 it may be not considered yet by literature since it is a less mature technology. When it comes to resins, it is difficult to assess which one is mostly used or discussed from Table D.1; however, industry experts mentioned PFA resin as the most mature bio-resin solution (Interviews 3, 7, 9 and 10). For non-bio-based resin, phenolic or epoxy resin is nowadays the most commonly used in conventional composites with glass fiber reinforcement. The industry professional said that phenolic resin has worse mechanical properties than epoxy; however, it is cheaper and regularly used in aircraft interiors (Interviewee 10). The academic expert said that phenolic resin has better flammability resistance than epoxy (Interviewee 6). From Table 4.2 it can be seen that phenolic resin has the lowest carbon footprint; however, it is not bio-based resin on contrary to PFA resin.

Further, in the previous sections of this chapter, it was observed that the main reason why bio composites are not used in aviation yet is the fact that aviation regulations are very strict, and according to both academic and industry experts, flammability requirement is the main challenge for aircraft interior materials (Interviewees 3 and 6). This statement is widely confirmed by literature, for instance, in the researches of Bachmann *et al.*, 2017; Chai, 2014; Santos *et al.*, 2016. That is why further research should be done on materials that already passed the flammability tests. EcoTechnilin and Lufthansa Technik with Bcomp managed to develop such materials; however, there is no publicly available data on what are the detailed sub-materials in these composites and what is the environmental impact of these. That is why two influential public papers were found - Gomez-Campos *et al.*, 2021; Vidal *et al.*, 2018. Both papers conducted LCAs on bio composite panels for aircraft interiors, where flax fiber was used instead of synthetic fiber. The summary of the assessed materials and environmental impacts from both papers is presented in Table 4.3. The term 'skins' and 'core' are explained in the section 4.1 in Figure 4.1b.

Table 4.3.: Summary of LCAs of Vidal *et al.*, 2018 and Gomez-Campos *et al.*, 2021. Abbreviations: PEI - polyetherimide, PLA - polylactic acid, EP - epoxy.

Reference		Vidal *et al.*, 2018				Gomez-Campos *et al.*, 2021	
Bio Composite Panel	**Panel Name**	Geopolymer Panel	Biopolymer Panel	PP Panel	PLA Panel	Biocomposite Panel	
	Panel Composition	Core - PEI Skin - flax/geopolymer	Core - PEI Skin - flax/bioplymer	Core - PEI Skin - PP	Core - PEI Skin - PLA	Core - Flax/EP Skins - Flax/EP	
Conventional Panel	**Panel Composition**	Core - honeycomb of aramid fiber paper Skin - prepreg of glass/phenolic				Core - honeycomb of aramid fiber paper Skin - glass/EP	
Change in Carbon Footprint		-6012 kgCO2eq	-2871 kgCO2eq	-114 kgCO2eq	-508 kgCO2eq	+18%	-34%
Change in Cumulative Energy Demand		-81777 MJ	-39164 MJ	-1784 MJ	-7160 MJ		
Change in weight		-0,61kg (-30.5%)	-0,29kg (-14.5%)	-0,01kg (-0.5%)	-0,05kg (-2.5%)	+14%	
System Boundary		Cradle-to-grave				Cradle-to-grave	Cradle-to-gate

As stated in Table 4.3 the difference between Gomez-Campos *et al.*, 2021 and Vidal *et al.*, 2018 is that Gomez-Campos *et al.*, 2021 are assessing panel fully made from flax fiber reinforced epoxy, while Vidal *et al.*, 2018 are using plastic in a core of a panel; however, in the skin, they are using solely bio-based materials in the case of geopolymer and biopolymer panels. The results of these two papers are significantly different. On one hand, Gomez-Campos *et al.*, 2021 conclude that the bio composite panel end up with a higher weight by 14% which offsets any environmental gains from manufacturing and the end-of-life stage. On the other hand, Vidal *et al.*, 2018 conclude that the weight of bio composite panels is lower than the weight of the conventional panel and there are significant environmental gains from using bio composite panels. The difference might stem from the fact that Vidal *et al.*, 2018 are using a plastic core in their panel, which may be the key to achieving lower weight. Additionally, it is difficult to compare the values. Gomez-Campos *et al.*, 2021 are using only percentage differences and not stating what is the carbon footprint of the conventional panel. On the contrary, Vidal *et al.*, 2018 use solely the net environmental benefits of sustainable panels, but again do not state what is the total carbon footprint of conventional panels. Therefore, it is difficult to determine the reason for the difference in results between these two papers. That is why deeper environmental analysis is needed to determine environmental benefits which are presented in chapter 5.

4.5.2. MATERIAL COSTS

In the literature, bio composites are considered to be less expensive than composites which are using synthetic fibers. Bachmann *et al.*, 2017 shows the prices of synthetic (carbon, glass, aramid) and natural fibers (flax, hemp, jute, ramie) and the prices of natural fibers are significantly lower, where jute and hemp are the cheapest. In particular, Flax's price is 2.1-2.4 $/kg, Hemp's is 1.0-2.1 $/kg, Jute's is 0.35-1.5 $/kg and Ramie's is 1.5-2.5 $/kg. Since the prices are low and similar to each other, it cannot be concluded which fiber would be the best solution judging solely on material costs. According to an expert working with bio composites, flax fiber is more expensive than hemp fiber; however, the mechanical properties of flax fiber, especially put in a unidirectional manner, are much better when it comes to stiffness and strength (Interviewee 1). When it comes to resins, industry professionals from Collins Aerospace said that PFA resin is comparable in cost to epoxy resin (Interviewees 9 and 10). It might be more expensive at the beginning of production, but the price is predicted to go down when more people start using it. Additionally, phenolic resin is mentioned to be cheaper than epoxy (Interviewee 10).

4.5.3. Recyclability

When it comes to the recyclability of bio composite the opinions within the selected literature are divided. Some papers say that bio composite is easy to recycle or dispose of; however, some says that currently there is no recycling possibilities and considers only incineration end-of-life scenario for these materials. In particular, Vidal *et al.*, 2018 consider in their LCA mechanical recycling, where the recycled materials are reduced in size and reused as fillers for different materials. They also consider the incineration scenario. Arockiam *et al.*, 2018 state that the resin used in EcoTechnilin's FlaxPreg T-UD FR is biodegradable or recyclable. On the other hand, Gomez-Campos *et al.*, 2021 in their LCA claim that flax fiber reinforced epoxy panels are considered hazardous waste and recyclability is currently not feasible. Deng *et al.*, 2014 claim that "material recycling for FRPs (Fiber Reinforced Plastics) is very challenging", and that some sources state almost zero percent of FRPs recyclability; hence, incineration is regarded as the most mature scenario. Moreover, the authors say that natural fiber contrary to glass fiber is combustible and contributes to higher heating value per weight.

Since based on available information the conclusion is hard to be reached, the experts were asked for an opinion through interviews. The industry expert from EcoTechnilin points out that the best solution (and the most common practice) right now is to burn it and recover the energy from incineration (Interviewee 2). The fact that bio composites have a high heating value which is why the burning option is not that harmful to the environment is also confirmed by the academic experts (Interviewees 4, 5 and 6). On the other hand, an industry professional from Lufthansa Technik is saying that landfilling or reusing is the best option for the environment as the production of the products from bio composites takes the CO2 from the environment so it is better to keep it there instead of burning (Interviewee 3). Moreover, the professional from Bcomp says that recyclability depends on the used resin and when thermoset resin is used (such as epoxy, phenolic and PFA resin) incineration is the only option; however, when the thermoplastic resin (such as PP and PLA resin) is used it can be mechanically recycled and reused (Interviewee 8). This is confirmed by the expert from Collins Aerospace (Interviewee 7). Additionally, another professional from Collins Aerospace said that PFA is non-biodegradable, but PLA is; however, it has worse properties; therefore, is not considered to be a viable option for now (Interviewee 10).

Lastly, the common practices of aircraft seats disposal were discussed in the Sustainability Council of Collins Aerospace Interiors in North Carolina (9-11 May 2023). It was concluded that there is little knowledge of airlines' disposal practices. However, it is known that two European airlines are giving their aircraft seats to disposal companies which are trying to make value from recycling/re-using/burning seats' parts (Collins Aerospace employee, personal communication, 9 May 2023).

To sum up, since most of the used resins are thermosets, it can be assumed that all the bio composites are currently not commonly recycled in the industry but incinerated. Therefore, based on that it cannot be concluded which material composition would be the best from that point of view.

4.5.4. DECISION ON BIO COMPOSITE FOR FURTHER ANALYSIS

Looking at three categories, the environmental impacts, material costs and recyclability it is concluded that flax fiber is mostly investigated as a reinforcement in bio composites. According to the industry professional from EcoTechnilin, it is the strongest of the considered natural fibers (Interviewee 2). Additionally, it is comparable in costs (professional from Bcomp, Interviewee 8) and has a lower environmental impact on the environment than glass fiber. Therefore, the research recognises this fiber to have the biggest potential to be used in aircraft interiors. When it comes to resin, PFA is the most commonly used one, the most mature, comparable in cost and with the lowest environmental impact. However, due to the specificity of the aviation industry and its requirements, it was concluded that environmental analysis of already developed materials for aircraft interiors purpose will be further developed. This is because of flame-retardant additives and other materials that are added to the composite to meet the requirements. Since the flax fiber/PFA composite data of already developed material was not found in the literature, the decision on the material was limited to the panels presented in papers Vidal *et al.*, 2018 and Gomez-Campos *et al.*, 2021. Based on the analysis of the two papers it was concluded that the most promising to be implemented in aircraft interiors bio composite is the **geopolymer panel** developed by Cayley project and investigated by Vidal *et al.*, 2018. This is because the geopolymer panel is the lightest of all the assessed panels in the article (Table 4.3). Its skins are prepregs composed of geopolymer resin, which is an inorganic thermoset resin from natural sources, and natural flax fiber reinforcements with a flame-retardant additive. Its core is made from foamed polyetherimide manufactured using non-ozone depleting blowing agents (Vidal *et al.*, 2018). To assure that this material meets aviation requirements for commercial flights, these were looked into.

REQUIREMENTS AND CERTIFICATION

According to Vidal *et al.*, 2018, the geopolymer panels were developed to fulfil the fire resistance requirements which are set by Federal Aviation Administration (FAA):

- Heat release: peak heat release rate ≤65kW/m2, and total heat release ≤65kW-min/m2
- Flammability: burn length ≤152mm, flame time ≤15s, and flaming time of drippings ≤3s.
- Smoke density: specific optical smoke density in the flaming mode ≤200.
- Smoke toxicity (toxic gases in ppm): HCL<150, HF<100, SO2<100, NOX<100, HCN<150, and CO<1000.

Arockiam *et al.*, 2018 said that the main concerns in regulations are about maintaining fire, smoke and toxicity (FST) standards. Therefore, it can be deduced that satisfying the listed above requirements is enough, and geopolymer panels can be used in aircraft interiors. However, a deeper analysis should be done in the area of regulations. Therefore, the experts were asked for an opinion. Since EcoTechnilin was the part of Cayley project, Interviewee 2 from that company was asked about the certification of their product FlaxPreg T-UD FR. He/she said that their material passed the FAR 25 fire retardant test. Therefore, the fire resistance of the geopolymer panel described by Vidal *et al.*, 2018 is confirmed since EcoTechnilin's product was used there. However, the professional from EcoTechnilin mentioned that it is not an official certification, since to do the official one client from the aviation industry is needed (Interviewee 2). The professional from Lufthansa Technik mentioned a similar situation in their company (Interviewee 3). The AeroFLAX material passed the fire resistance tests; however, to be officially certified the interested client is essential. This is because according to Collins Aerospace employees, the official certification in the aviation industry is carried out on a ready product, and not on the material itself (Interviewees 10 and 12). So the fact that material passes the tests is the first step in the development stage; however, it is not the official green light for usage in an aircraft. The described certification practices are confirmed by the author's direct observation and personal communication in the test centre in Winston-Salem (10 May 2023, North Carolina, USA). The final product needs to meet various requirements, where flammability, heat release, smoke density and smoke toxicity (FAR 25.853) are one of many tests that are done on a ready-seat product (direct observation, 10 May 2023). The tests are conducted by Collins Aerospace employees in special company facilities, where tests are video-recorded. When the product passes the test, the results with video recording are sent to the certification authorities which validate the test and certify the product (Collins Aerospace employee, personal communication, 10 May 2023). Therefore, it can be concluded that until any aviation company decides to develop a product from bio composite the official certification will not be conducted.

To sum up, the results from this section are feeding the next chapters of sustainability assessment. Because of recognized drivers, the analysis of predicted environmental and economic benefits for the particular case of Collins Aerospace business class seat needs to be developed. Also, the realized discrepancies in the development stage of bio composite technology in the automotive and aviation industry give evidence that there is a significant difference in the suitable materials for these two industries. Therefore, it was concluded that for further analysis the material that already exists and meets the strict requirements for aircraft interiors should be chosen. Additionally, the pattern analysis determined the time in which experts anticipate the innovation implementation in commercial aviation, which helps to establish the time frame for economic assessment. Next, the comparative analysis of different fibers and resins that can be used in bio composite resulted in the decision on the material - geopolymer panel - which is an example of a suitable choice for aircraft interiors and is further considered for environmental and economic assessment. In addition, that section helped in recognition of the challenges in the environmental data collection process and finding a solution of further search in one which is a reliable database - Granta EduPack (2022 R1). Also, it helped to establish the most reliable recycling scenario using data from literature and interviews. Lastly, the interviews served as an indication of the price difference between conventional and bio composites which was a valuable insight for economic assessment.

5

THE ENVIRONMENTAL ASSESSMENT

The purpose of the section is to create an environmental assessment of chosen bio composite material using LCA methodology. The tool has been chosen because it was determined to be the most suitable for such a purpose. Firstly, the Literature Study in chapter 2 presented that this is the most commonly used method for an environmental assessment. Secondly, for the assessment of currently developed bio composite materials industry professionals are also using LCAs (Interviewees 2, 3, 7 and 8). Additionally, an expert in transport policies said that "LCA makes the most sense because it's a relatively old method already [...] I think there are also good international standards and international databases. Now I would say that the LCA would be a nice and very useful tool to use" (Interviewee 11). The LCA is conducted using ISO 1404X standards, which divides the assessment into four stages described in section 3.3.1. This chapter is divided accordingly to the standard's division.

This study is the *comparative, fast-track LCA* for chosen bio composite panel - **geopolymer panel** and conventional composite panel (both specified in Table 4.3). *Fast-tracked* because only one environmental impact from LCA impact categories is considered - Carbon Footprint. In addition, energy consumption and water usage are also included, which are not impact categories but process inputs. *Comparative* because only the difference in carbon footprint, energy consumption and water usage are calculated when instead of conventional composites the bio composites are used in Collins Aerospace business class seats. Therefore, it is not a full Life Cycle Assessment with all environmental impacts measured and with full seat product analysis. Hence, the results are in comparative, not absolute values. Finally, this chapter concludes what is the environmental impact of replacing conventional materials with innovative bio composite materials.

The LCA is using data and methodology of Vidal *et al.*, 2018 research; however, it is adjusted to the Collins Aerospace product. The difference is that Vidal *et al.*, 2018 analysed the material when used in aircraft sidewall panels, here these are applied in some parts of an aircraft seat, the product of Collins Aerospace. Additionally, different environmental data for inventory analysis is taken. Here, one database is used - Granta EduPack (2022 R1), when on the contrary Vidal *et al.*, 2018 is using data from research papers or direct measurements. Because of these differences, the separate LCA research needed to be developed which is presented in that section.

5.1. Goal and Scope Definition

The study aims to calculate the environmental impacts of the bio composite panel for aircraft interiors during the whole life cycle and to compare it with the conventional honeycomb panel. The application of bio-based composite is in some elements of aircraft business seats (product of Collins Aerospace), which currently are made from glass fiber/phenolic resin composite with aramid paper honeycomb. Since the goal of this study is to compare conventional materials with bio composite materials, the full LCA is not developed. Only the comparison of the parts that are exchanged is made, with the assumption that the rest stays the same. Therefore, this study cannot serve as the seating product LCA, it is solely developed for a comparison of the environmental impacts of different materials. Hence, only the difference in environmental impact is calculated.

The comparison is made between the conventional panel and the bio-based geopolymer panel developed by the Cayley project. The materials presented in both panels are shown in Table 5.1. More detailed information about the materials composition is explained in Vidal *et al.*, 2018. The clarification of composite components is presented in Figure 4.1b.

Table 5.1.: Material composition of conventional and geopolymer composite based on the research of Vidal *et al.*, 2018

	Conventional Composite		**Bio Composite**	
	Materials	**Weight [kg]**	**Materials**	**Weight [kg]**
Core	Aramid Fiber Paper	0,41	Polyetherimide (PEI)	0,09
Skins, matrix	Phenolic Resin	0,42	Geopolymer Resin (synthesized with metakaolin, an alkali metal hydroxide and silicate solution)	0,6
Skins, reinforcement	Glass Fiber (mixture of the E-glass)	0,73	Flax Fiber Yarn	0,22
Skins, flame-retardant coating	DecaBDE	0,07	Non halogenated	0,08
Decorative film	PVC film	0,37	PVC film	0,39
TOTAL		2		1,38

The conventional panel used in Vidal *et al.*, 2018 and presented in Table 5.1 is assumed to be the same or very similar to what Collins Aerospace is using. This is the case since Collins Aerospace employees said that they are using composites from Nomex honeycomb (which is a trademarked material using aramid fiber paper core) with phenolic/glass fiber skins (Interviewees 7, 9 and 10). Therefore, for the purpose of that research, it is justified to assume that the conventional panel used in Vidal *et al.*, 2018 research is the same as the one Collins Aerospace is using.

This research is a **cradle-to-grave** LCA and the **system boundary** is described by the considered phases of the life cycle presented in Figure 5.1.

When it comes to a **functional unit**, it is one business class seat used in Boeing 787-8, for 5 years. 5 years of seat usage was chosen because it is observed by Collins Aerospace lifetime of a seat, since on average after 5 years of aircraft operation interior is changed. This choice is justified by Dale Brosius of Brosius Management Consulting (Brighton,

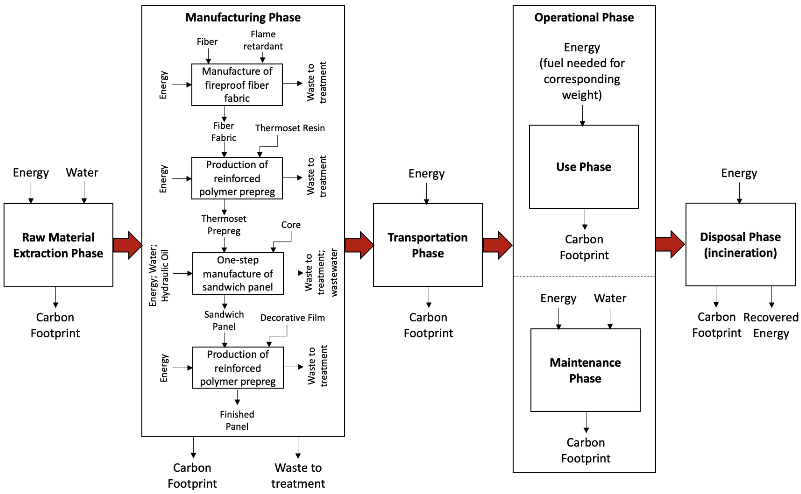


Figure 5.1.: System boundary of the LCA. Image edited, sourced from Qian *et al.*, 2013.

Mich.) which says that interior components have a service life of between three to seven years (Staff, 2006). The short lifetime of seats is in detail described in the Problem Definition in section 1.1.1.

The **data source** of environmental impacts of materials is mainly the Granta EduPack (2022 R1) database which is a product of Ansys. The program has data on the carbon footprint, energy requirement and water usage of raw material extraction, the carbon footprint from incineration and recovered energy from burning. In case when a material is not found there, literature is looked into. In particular, Granta EduPack covers the raw material extraction phase, disposal phase and new materials needed for the maintenance phase. Moreover, data in Granta EduPack is stated as ranges. During this research, the analysis was carried out to see the difference in total impact when a lower and then a higher number from the range is taken. In the effect, the differences in the two cases in total impacts were less than 0,5%. Therefore, it was concluded that only one number will be taken from the database - the higher one to show the worst-case scenario. In addition, the carbon footprint for the transportation phase and fuel burn during the use phase is taken from the Idemat2022 database which is the product of TU Delft.

Lastly, there are a few **limitations** in this LCA which are pointed out below.

- Data presented in Granta EduPack does not have a location of the production site specified; therefore, the real carbon footprint might differ depending on where geographically the material is produced/incinerated,
- Some environmental data in Granta EduPack is marked as 'estimated', which means that it is calculated using models instead of direct measurements or using different reliable database. It might be the case that the quality of such data is lower. If this is the case for any data taken from the database it is further stated,
- Only one impact category is taken into account in the LCA, along with energy requirement and water usage which are not impact categories of the LCA but the

additional environmental data. Because of that it is possible that the assessment of other impact categories would result in different conclusions on the technology,
- The fuel burn model discussed in the use phase excludes the take-off, landing and taxiing stages of flight; therefore, the given here fuel saved underestimated the real number which in the reality would be even higher,
- Disposal phase was assumed to be incineration (based on current industry patterns, interviews and literature discussed in section 4.5.3), where the energy from burning is recovered based on the Global electricity mix. This disposal method was identified as the most realistic scenario right now. Therefore, other end-of-life scenarios such as recycling, re-using or landfilling were not considered in this research. However, in a few years the technology might change and recycling for bio composites might be easily available.

5.2. Inventory Analysis

5

In this section information on inputs and outputs for each stage of the life cycle was gathered. The section is divided based on all the life cycle phases of a product.

5.2.1. Raw Materials Extraction Phase

Data on the exact composition of conventional and bio composite panels were taken from Vidal *et al.*, 2018. The material composition with the weights and impacts per 1 kg of the particular material with data source is presented in Appendix E in Table E.1.

For the inventory phase, Granta EduPack was chosen as the source. This is because the inventory data from papers that Vidal *et al.*, 2018 research was referencing was either difficult to extract or non-available. It is the case for many LCAs as detailed and full environmental data is not easily available because it is not free. In addition, getting the environmental data from the LCAs of other researchers would be very time-consuming and it would be also prone to errors because each LCA is taking different assumptions in the considerations. Therefore, it was concluded that using one single database which is using consistent assumptions is a better option for this exercise. In case some material data was not available in Granta EduPack it is indicated in this thesis and the data is looked for in the literature. Additionally, when only electricity requirement data was found it was translated to carbon footprint using the appropriate electricity mix, which was similar practice in the LCA of Khoo *et al.*, 2010. In the case of the raw material manufacturing phase, the carbon footprint of DecaBDE (flame-retardant) shown in Table E.1 was calculated using a US Electricity mix, due to the fact that skins of conventional panels are produced in the US (information from personal communication with Collins Aerospace employee specializing in composites). On the contrary, the carbon footprint of non-halogenated flame-retardant for bio composite was calculated using the EU electricity mix. That is because it is predicted that when bio composites for aviation will be produced these will be first manufactured in Europe, since the biggest players are placed in Germany (Lufthansa Technik), France (EcoTechnilin) and Switzerland (Bcomp).

5.2.2. Manufacturing Phase

In the manufacturing phase, two constituents were taken into account.

1. Energy requirement for manufacturing $1m^2$ of panel, taken from inventory made by Vidal *et al.*, 2018. Here, based on electricity requirement carbon footprint was calculated using the EU electricity mix for both panels.
2. Waste products of manufacturing $1m^2$ of panel, taken from an inventory made by Vidal *et al.*, 2018.

Data on energy requirements and waste products are presented in Appendix E in Table E.2. The details of the EU electricity mix are presented in Table F.1 in Appendix F. The EU electricity mix was chosen because according to Collins Aerospace employee composite panels are manufactured from already delivered skins and cores in Northern Ireland, Kilkeel. Carbon footprint, electricity and water usage for "Waste" products are taken from Granta EduPack. All the waste is assumed to be landfilled as in Vidal *et al.*, 2018, instead of wood and cardboard which is recycled. The numbers presented in Table E.2 are numbers for manufacturing $1m^2$ of each panel.

5.2.3. TRANSPORTATION PHASE

The transportation phase was divided into three steps:

1. Transportation of raw materials to a panel parts supplier,
2. Transportation of panel parts from supplier to Collins Aerospace manufacturing site,
3. Transportation of ready panel mounted in a seat from Collins Aerospace manufacturing site to the final client.

When it comes to step 1, the location of raw materials and the place of panel parts suppliers are usually very close to each other (Collins Aerospace employee, personal communication, April 2, 2023). Therefore, this stage is regarded to be negligible for the final LCA results. In addition, the result for both panels is predicted to be similar; therefore, would not have a significant impact on the final comparative results.

Step 2 is determined based on information from Collins Aerospace employees about current composite suppliers. The given information was that the core of conventional composite it transported from Michigan (USA) to Kilkeel (Northern Ireland), while skins were from Boston (USA) to Kilkeel. For bio composite, the routes were assumed based on available data. The transport of the core was assumed to be the same as the transport of the conventional panel core. This is because there is big uncertainty of that; therefore, determining it as the same as for another panel would not make a difference in the final, comparative score. When it comes to skins, the manufacturers of bio composite skins for the aviation industry are not established yet. Therefore, the main players that are currently developing bio composites for aircraft interiors were considered. Lufthansa Technik, based in Hamburg was chosen to be the manufacturer of the skins. The inventory data for transportation in step 2 with the indicated mode of transportation modes is presented in Appendix E in Table E.3.

Lastly, step 3 was determined based on a private conversation with a Collins Aerospace employee. The main route was determined in which the ready seat is transported to Boeing, from Kilkeel where Collins Aerospace has its factory site. Only transport to Boeing is considered since the investigated aircraft is Boeing 787-8. Additionally, it was mentioned by Collins Aerospace employee that in 10% of cases, the products are transported by aircraft when the delivery needs to be rushed. Therefore, aircraft transportation in

10% of cases was included in calculations. The transportation routes are the same for both panels. The data is summarized in Appendix E in Table E.4.

The carbon footprint and energy data for all the transportation steps were taken from the Idemat2022 database and are presented in Appendix E in Table E.5.

5.2.4. USE PHASE

In the use phase, the emissions from fuel burn for which a material weight is corresponding is calculated. Hence, to calculate these the **fuel burn model** needs to be developed which is the exercise of this section. From the inventory of the raw material extraction phase, it is known that $1m^2$ **of conventional panel weighs 2kg, while the same area of bio composite panel weighs 1,38kg** (Vidal *et al.*, 2018). The used equations for fuel burn are taken from Collins Aerospace's previous fuel burn models and used in consultancy with the internal expert.

First, the technical data was gathered for Boeing 787-8 for which this analysis is developed. These are presented in Table 5.2.

Table 5.2.: Technical data for B787-8

Nr	Symbol	Description of data	Value	Data source
1	OEW	Operating Empty Weight [kg] [1]	119950	Airliners, 2022
2	-	Payload [kg] [2]	32420	Own calculations
3	-	OEW + Payload [kg] [3]	171544,8	Own calculations
4	L/D	Lift-to-drag Ratio [-] [4]	20,8	Lissys, 2005
5	TSFC	Total Specific Fuel Consumption [kg/Ns] [5]	0,0000143	Wikipedia, 2023
6	v	Cruise speed [m/s]	250,8	Airliners, 2022
7	t_{av}	Average flight time [h]	9,15	2019 flight data
8	R_{av}	Average distance [km]	8236,9	2019 flight data
9	N_s	Number of business class seats [-]	18	SeatGuru, n.d.
10	-	Seat occupancy rate [-]	79%	Collins Aerospace data
11	-	Hours of flying per day [h]	15	Collins Aerospace assumption
12	-	Days of flying per year [days]	360	Collins Aerospace assumption
13	T	Lifetime of seat [years]	5	Collins Aerospace assumption
14	-	Number of flights per day	1,64	Own calculations
15	N_{f5}	Number of flights in seat lifetime T (5 years)	2950,15	Own calculations
16	$m_{conv_{1s}}$	Weight of all conventional composite panels in 1 business class seat	9,04kg	Collins Aerospace data
17	$m_{bio_{1s}}$	Weight of all bio composite panels in 1 business class seat	6,29kg	Collins Aerospace data
18	m_{conv}	Weight of $1m^2$ of conventional composite panel	2kg	Vidal *et al.*, 2018
19	m_{bio}	Weight of $1m^2$ bio composite panel	1,38kg	Vidal *et al.*, 2018

[1] The weight of the aircraft structure with furnishing and systems that are integral parts of the aircraft, and cabin crew, seats, galley structure, catering equipment etc. (Airbus, 2002)
[2] The weight of passengers, their bags and reserve fuel (Airbus, 2002)
[3] Also called Zero Fuel Weight (ZFW) (Airbus, 2002)
[4] Ratio specific for an aircraft
[5] Number specific for an engine. Since B787-8 can fly with different engines, here one case was chosen and the data is given for Rolls-Royce Trent 1000

When it comes to data source '2019 flight data', this is the data of all flights that happened in 2019, so before COVID-19. The data was accessed from the company that

Collins Aerospace owns and which gathers flight data. Based on this the average flight time and distance were calculated for all B787-8 flights in 2019 which were long-haul flights (over 6 hours flight). Only long-haul flights were selected as the analysed product is business class seat, which is not always present in short-, or medium-haul flights.

For calculated data in Table 5.2 are explained below where Nr in squared brackets corresponds to the Nr in the first column in Table 5.2.

Nr 2 OEW+Payload $= 6500kg + (274 * [Nr9] * 120kg) = 32420kg$, where

- 6500kg - reserve fuel weight [kg]
- 274 - number of all the seats in B787-8 (source: SeatGuru, n.d.)
- 120kg - passenger and fuel weight [kg]

Nr 3 OEW+Payload $= [Nr1] + [Nr2] = 119950 + 32420 = 171544,8kg$
Nr 14 Number of flights per day $= [Nr11]/[Nr7] = 15/9,15 = 1,64$
Nr 15 Number of flights per year $= [Nr14] * [Nr12] * [Nr13] = 1,64 * 360 * 5 = 2950,15$

The second step was to calculate the TOW (Total Operating Weight) of an aircraft when conventional composites are used, which is the current situation, and the TOW of an aircraft when bio composites are used. In order to calculate TOW the Breguet Range Equation was used which is the following for the current case (when conventional composites are used):

$$TOW_{conv} = (OEW + Payload) * e^{(\frac{R*g*TSFC}{v*L/D})}, \tag{5.1}$$

where g is the standard acceleration of gravity.

Since when using bio composite the total weight of an aircraft is different, TOW_{bio} for that case needs to be separately calculated. In such a case from OEW+Payload, the saved weight from replacing conventional panels with bio composite panels in all the business class seats is calculated. To know these, the weight of conventional composites in the representative Collins Aerospace product of business class seat was calculated, based on Bills of Materials received from the company. Hence, the weight of all conventional composites in a Collins Aerospace business class seat is 9,04kg. It is also known, that $1m^2$ of conventional panel is 2kg, and $1m^2$ of bio composite (geopolymer panel) is 1,38kg (Vidal *et al.*, 2018). Therefore, it was calculated that the bio composite panel is 31% lighter $((1,38-2)/2)$. So, when replacing all the conventional composites with bio composites in Collins Aerospace one business seat product, the saved weight would be $\Delta m_{1s} = 9,04kg - (9,04kg * (100\% - 31\%)) = 9,04kg - 6,29kg = 2,76kg$. Therefore, to calculate the TOW when bio composites are used in all the business class seats in B787-8 the following equation was used:

$$TOW_{bio} = ((OEW - \Delta m_{1s} * N_s) + Payload) * e^{(\frac{R*g*TSFC}{v*L/D})}, \tag{5.2}$$

where the symbol with values are given in Table 5.2, and $\Delta m_{1s} = 2,76kg$ is the saved weight on one business class seat, as calculated above.

The last step is to know the fuel weight used during a flight. For conventional composite, it is the difference between starting and landing weight which is:

$$m_{f_{conv}} = TOW_{conv} - (OEW + Payload). \tag{5.3}$$

For the bio composite, it is important to remember to subtract also the saved weight by replacing panels in 18 seats in order to have solely the fuel weight difference. Therefore, the following equation was used:

$$m_{f_{bio}} = TOW_{bio} - ((OEW - \Delta m_{1s} * N_s) + Payload). \tag{5.4}$$

The results of TOW and Fuel Weight are presented in Table 5.3.

Table 5.3.: Results of fuel weight calculations

Data	**When conventional composites are used**	**When bio composites are used**
TOW	$TOW_{conv} = 190144kg$, equation 5.1	$TOW_{bio} = 190082kg$, equation 5.2
Fuel weight required for flight - m_f	$m_{f_{conv}} = 37774kg$	$m_{f_{bio}} = 37762kg$
Saved fuel weight, per flight Δm_f	$\Delta m_f = 12,31kg$ when using bio composites	

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To translate saved fuel to environmental impacts the carbon footprint and energy of burning 1kg of aircraft fuel, kerosene, was taken from an inventory database. The numbers are presented in Table 5.4.

Table 5.4.: Environmental impact data for use phase

	Carbon Footprint	**Energy**	**Source**
Burning of 1kg of aircraft fuel	$CF = 3,57 \frac{kcCO2eq}{\text{1kg of used fuel}}$	$E = 52,9 \frac{MJ}{\text{1kg of used fuel}}$	Idemat2022 (kerosene)

Lastly, in order to know the carbon footprint for which the weight of 1 panel and in turn all the panels in 1 seat (to be consistent with the functional unit) is responsible for during the seat lifetime the following calculations were conducted. First, the methodology for conventional composite is presented where the result shows UP_{CFconv} which is for **U**se **P**hase **C**arbon **F**ootprint from **conv**entional panels in 1 business class seat for 5 years of operation.

$$UP_{CFconv} = \frac{\text{CF} * m_{f_{conv}} * m_{conv_{1s}} * N_{f5}}{TOW_{conv}} = \frac{3,57 * 37774 * 9,04 * 2950,15}{190144} = 18924kgCO2eq \tag{5.5}$$

Where:

- CF - carbon footprint for burning 1kg of kerosene [$\frac{kgCO2eq}{\text{1kg of used fuel}}$] (Table 5.4)
- $m_{f_{conv}}$ - the weight of fuel required for flight, when conventional composites are used [kg] (Table 5.3)
- $m_{conv_{1s}}$ - the weight of all conventional panels in 1 business seat [kg] (Table 5.2)
- N_{f5} - number of flights in 5 years (Table 5.2)

The methodology for bio composite calculations is similar; however, there is one important step that requires more attention. The weight of fuel that is saved because of the reduced weight of seats needs to be included in the calculations. Here, for simplicity reasons, this subtraction will be done on the weight of all the bio composites in 1 seat. Hence, from the weight of all bio composites in 1 seat, the fuel weight saving for which 1 seat is responsible for was subtracted. The calculation looks the following.

$$m'_{bio_{1s}} = m_{bio_{1s}} - \frac{\Delta m_f}{N_s} = 6,29kg - \frac{12,31kg}{18\text{seats}} = 5,6kg \tag{5.6}$$

Where:

- Δm_f - saved fuel weight, per flight [kg] (Table 5.3)

Next, the UP_{CFbio} is calculated which is the **U**se **P**hase **C**arbon **F**ootprint from **bio** composite panels in 1 seat for 5 years of operation.

$$UP_{CFbio} = \frac{\text{CF} * m_{f_{bio}} * m'_{bio_{1s}} * N_{f5}}{TOW_{bio}} = \frac{3,57 * 37762 * 5,6 * 2950,15}{190144} = 11721kgCO2eq \tag{5.7}$$

For calculating the energy consumption for which panels are responsible, the exact same equations as 5.5 and 5.7 were used, but instead of CF the value for consumed energy when using 1kg of fuel E from Table 5.4 was used.

Lastly, it is important to mention that the fuel savings and saved emissions are as above only when an airline is not substituting saved weight with an additional payload. For instance, an airline is not putting more seats because the weight of an aircraft is lower when using bio composites.

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5.2.5. MAINTENANCE PHASE

Using the data from Vidal *et al.*, 2018 it was assumed that 10% of panels per year need to be repaired due to worn decorative PVC film. The number of panels in an aircraft (with 18 business class seats) was calculated using the equation:

$$\frac{N_s * m_{conv_{1s}}}{m_{conv}} = \frac{18\text{seats} * 9,04kg}{2kg} = 82\text{panels}. \tag{5.8}$$

This translates to 10% $*$ 82panels $*$ 5years = **45 panels** which are predicted to be maintained during 5 years of operation. For bio composite panels this number is the same, as the maintenance rate of PVC film is predicted to not change after panels replacement.

Next, the environmental burden from (1) raw material extraction, (2) manufacturing, (3) transportation and (4) disposal of additional PVC film for 45 panels is calculated. The used equations for each of these phases are explained in detail in Appendix G in Table G.6. Lastly, the results of the impact assessment are divided by the number of business class seats in an aircraft (18 seats) to calculate the environmental burden by one seat.

5.2.6. DISPOSAL PHASE

In the disposal phase, full composite incineration with energy recovery was assumed. This is the case since according to industry and academia experts it is currently the most common practice in the automotive industry (Interviewees 2, 4, 5, 6 and 8). Here the following inventory data was gathered:

1. Carbon footprint emitted while burning composite (source: Granta EduPack),
2. Energy recovered (source: Granta EduPack),
3. Carbon footprint saved due to recovered energy, calculated using Global electricity mix (Appendix F).

Global electricity mix was chosen because of the unknown place of seat disposal. This is due to the fact that the airlines that Collins Aerospace is serving are from around the world; therefore, the place of incineration can be anywhere; hence the global average was taken. The inventory data from the disposal phase are presented in Appendix E in Table E.7 where electricity and carbon footprint are shown as in the database, so per 1kg of incinerated material.

5.3. IMPACT ASSESSMENT

All the environmental impacts presented in that section are calculated per functional unit, which is **per amount composites in 1 business class seat of Collins Aerospace which is used for 5 years**. The amount of conventional composites is calculated based on Bills of Materials of the current seating product of Collins Aerospace. The amount of bio composite is calculated in a way that the volume of composite panels stays the same as it is currently; however, due to the fact that bio composites are 31% lighter than conventional composites, the weight of these was reduced by that number. **Finally, all the conventional composites in 1 business class seat weigh 9,04kg, while all the bio composites in 1 business class seat weigh 6,29kg.**

5

This section is divided into two parts. First, the difference in total environmental impact from all life cycle phases is presented. Second, the comparison of conventional composite and bio composite is done by looking at all life cycle stages separately. All the detailed data of particular impacts in particular life cycle phases are presented in Appendix G.

First, the whole life cycle comparison between conventional composite panels and bio composite panels used in one business class seat for 5 years is conducted. The results are presented in Figure 5.2.

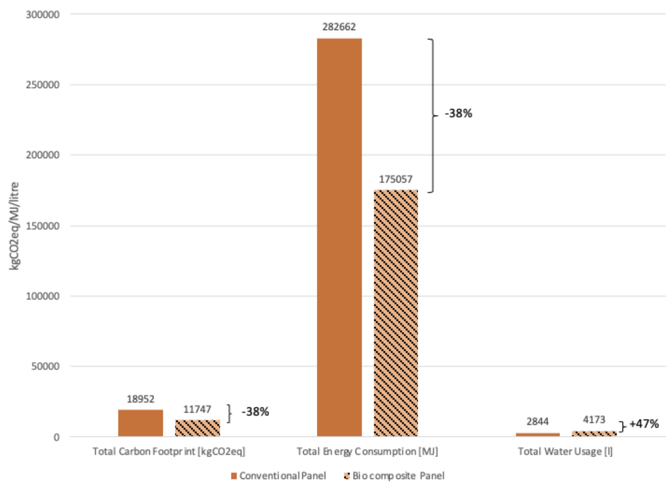

Figure 5.2.: Environmental impacts of the whole life cycle of conventional and bio composite in one business class seat, for 5 years of usage

From Figure 5.2 it can be seen that when it comes to carbon footprint and energy requirement, the usage of bio composite (geopolymer panel) has reduced environmental impact by 38%. It translates to a total reduction of 7205kgCO2eq and 107605MJ when exchanging conventional composites with bio-based composites in one business class seat which is used for 5 years. However, when it comes to water usage, bio composite during its lifetime needs 47% more water than conventional composite, which is an addition of 1330 litres of water. This is the case, as the production of flax fiber is a very water-demanding process which can be seen from inventory data in Table E.1. This is also confirmed by the industry expert from Lufthansa Technik, which mentioned that in their LCA calculations of AeroFlax, water usage is the only environmental impact where bio composite is worse than conventional from glass fiber/phenolic composite (Interviewee 3). The exact values and the differences in impacts are stated in Table 5.6.

Second, the assessment is done by the life cycle phases and the results are presented in Table 5.5. There is a value presented and a percentage which says for how much the particular phase is responsible when looking at all the life cycle phases. The graphs representing values in the Table 5.5 are presented on Figures 5.3, 5.4 and 5.5. As can be noted, in the cases of both materials, the use phase, which is included in the operational phase is contributing to more than 99% of the total carbon footprint and energy consumption. It is confirmed in Gomez-Campos *et al.*, 2021 research where it was concluded that the environmental performance of both bio composite and conventional panels are essentially shaped by the use phase. That research stated that all the phases instead of the use phase are negligible for the assessment of both panels. Vidal *et al.*, 2018 research came to a similar conclusion, as the use phase contributed by 98% to the overall impact for every aircraft panel and endpoint impact category. The same trend can be seen in the results in Table 5.5.

All the values and their comparisons between phases are presented in Table 5.6, where it can be seen that when it comes to carbon footprint and energy consumption, bio composites are better for the environment than conventional composites in the raw material extraction phase (-69% kgCO2eq, -76% MJ), transportation phase (-31% kgCO2eq, -29% MJ), and use phase (-38% kgCO2eq and MJ). On the contrary, are worse for the environment in the manufacturing phase (+29% kgCO2eq, +7% MJ), in the maintenance phase (+6% kgCO2eq and +8%MJ) and disposal phase when incineration is considered (+54% kgCO2eq, +56% MJ). When it comes to water usage in all phases bio composites are a bigger burden for the environment.

Table 5.5.: Environmental impacts with the contribution of each life cycle phase, for the amount of both composites used in one business class seat, for 5 years

	CARBON FOOTPRINT [kgCO2eq]				ENERGY [MJ]				WATER [l]			
	Conventional Panel		Bio Composite Panel		Conventional Panel		Bio Composite Panel		Conventional Panel		Bio Composite Panel	
	Value	%	Value	%	Value	%	Value	%	Value	%	Value	%
Raw Material Extraction Phase	45	0,24%	14	0,12%	954	0,34%	232	0,13%	2595	91,27%	3895	93,34%
Manufacturing Phase	22	0,12%	29	0,24%	348	0,12%	374	0,21%	63	2,22%	83	0,05%
Transportation Phase	11	0,06%	7	0,06%	940	0,33%	670	0,38%	-	-	-	-
Use Phase	18924	99,85%	11721	99,78%	280411	99,20%	173683	99,22%	-	-	-	-
Maintenance Phase	-2	-0,01%	-2	-0,02%	148	0,05%	160	0,09%	185	6,51%	195	0,11%
Disposal Phase	-48	-0,25%	-22	-0,19%	-139	-0,05%	-62	-0,04%	-	-	-	-

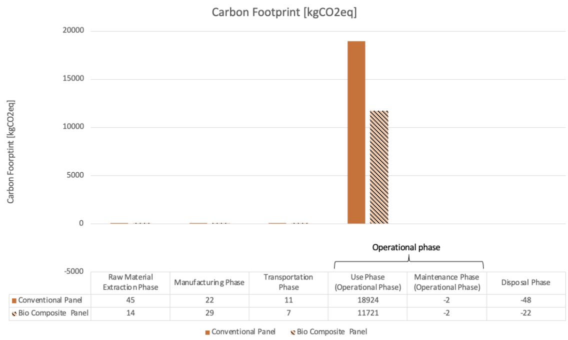

Figure 5.3.: Carbon footprint by life cycle phases of conventional and bio composite in one business class seat, for 5 years

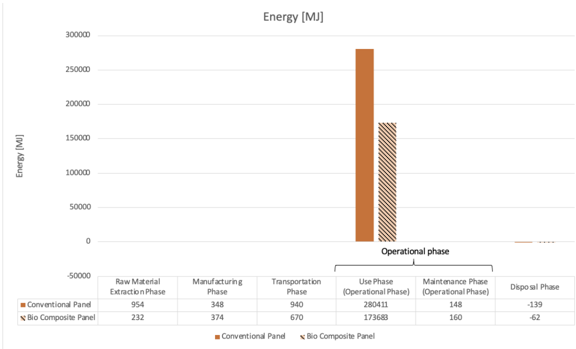

Figure 5.4.: Energy consumption by life cycle phases of conventional and bio composite in one business class seat, for 5 years

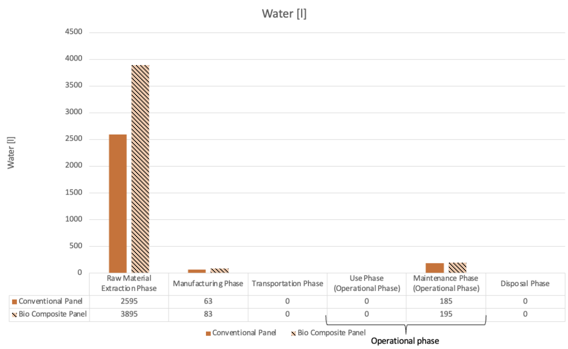

Figure 5.5.: Water usage by life cycle phases of conventional and bio composite in one business class seat, for 5 years

Table 5.6.: Environmental impact of all life cycle phases with value comparison between materials, for the amount of both panels used in one business class seat per 5 years

	CONVENTIONAL COMPOSITE			BIO COMPOSITE			Difference [%]			Difference in value		
Life Cycle Phases	**Carbon Footprint [kgCO2eq]**	**Energy [MJ]**	**Water Usage [l]**	**Carbon Footprint [kgCO2eq]**	**Energy [MJ]**	**Water Usage [l]**	**Carbon Footprint**	**Energy**	**Water Usage**	**Carbon Footprint [kgCO2eq]**	**Energy [MJ]**	**Water Usage [l]**
Raw Material Extraction Phase	45	954	2595	14	232	3895	-69%	-76%	50%	-31	-721	1300
Manufacturing Phase	22	348	63	29	374	83	29%	7%	32%	6	26	20
Transportation Phase	11	940	-	7	670	-	-31%	-29%	-	-3	-270	-
Use Phase	18924	280411	-	11721	173683	-	-38%	-38%	-	-7203	-106728	-
Maintenance Phase	-2	148	185	-2	160	195	6%	8%	5%	0	11	10
Disposal Phase	-48	-139	-	-22	-62	-	54%	56%	-	26	77	-
TOTAL	**18952**	**282662**	**2844**	**11747**	**175057**	**4173**	**-38%**	**-38%**	**47%**	**-7205**	**-107605**	**1330**

5.4. INTERPRETATION

The LCA interpretation is divided into two parts. First, the evaluation of the results is provided. Next, the conclusions and recommendations are stated.

5.4.1. EVALUATION OF THE STUDY

The evaluation has two steps. First, the results from this LCA were compared to the results of two similar studies of Vidal *et al.*, 2018 and Gomez-Campos *et al.*, 2021. The comparison was made after changing the lifetime of the product and functional unit to be equal to the one in the studies. Next, the fuel burn model was validated.

COMPARISON TO THE ARTICLES RESULTS

The results from this LCA were compared to the results presented in the literature that was recognized to be highly relevant to this study.

First, the results were compared to Vidal *et al.*, 2018 research. In order to do so, the calculations needed to be adjusted in Excel in order to meet the same assumptions and functional units. Therefore, the lifetime was changed to 20 years (as in Vidal *et al.*, 2018) and the analysed functional unit was changed to be $1m^2$ of a panel. The effect was that the carbon footprint from the total life cycle of this study is 441kgCO2eq (7%) higher. Moreover, calculated here total energy is 14163MJ (17%) higher. Water usage was not assessed in Vidal *et al.*, 2018 research. The difference might stem from the fact that LCA of Vidal *et al.*, 2018 was using many primary data delivered from suppliers or directly measured. On the contrary, here the secondary data was gathered due to limited time. Additionally, different assumptions might contribute to different results. However, looking at the scale of calculations, 7% and 17% of difference in carbon footprint and energy consumption is a satisfying result; therefore, the calculations are concluded to be valid.

Additionally, the results were also compared to the second paper of Gomez-Campos *et al.*, 2021. Here only cradle-to-gate calculations could have been compared as for cradle-to-grave boundary in the paper the percentage difference was not stated. Therefore, only the raw material extraction phase and manufacturing phase were compared (as Gomez-Campos *et al.*, 2021 excluded the transportation phase). Gomez-Campos *et al.*, 2021 results conclude reduction of 34% of carbon footprint when using bio composite. The results presented here state a reduction of 37%. Hence, a +3% difference is recognized. When it comes to water usage the difference between calculations here and in Gomez-Campos *et al.*, 2021 are +30%. Energy consumption was not assessed in Gomez-Campos *et al.*, 2021 research. Therefore, it can be concluded that carbon footprint calculations are close to the calculations in the literature; however, there might be bigger uncertainty when it comes to the water usage results. The comparison is presented in Table 5.7.

Table 5.7.: Results comparison of this LCA and similar LCA's from literature

	Vidal *et al.*, 2018		**Gomez-Campos *et al.*, 2021**	
	Carbon Footprint [kgCO2eq]	**Energy [MJ]**	**Carbon Footprint [kgCO2eq]**	**Water Usage [l]**
Result of this research	-6453	-95940	-37%	50%
Result from literature	-6012,00	-81777,00	-34%	80%
DIFFERENCE	+7%	+17%	+3%	+30%
DIFFERENCE IN VALUE	+441	+14193	-	-

5

The remark was discovered when comparing the results of LCA to the chapter 4 with bio composite analysis. As was mentioned in 4.5.3, academic experts in interviews supported the statement that bio composites have high heating value; therefore, incineration with energy recovery is not that harmful to the environment (Interviewees 4, 5 and 6). However, from LCA analysis it can be concluded that in the disposal phase, more energy can be recovered from conventional composites. The reason behind such a result might be that the assessed composite in LCA had geopolymer resin, which has excellent fire resistance properties (Razak *et al.*, 2022); therefore, the energy from it cannot be recovered. On the contrary, a phenolic resin used in the conventional composite is combustible. The statement of Interviewees 4, 5 and 6 would be true when resin used in bio composite was made from combustible polymer, as glass fiber cannot be burned with recovered energy, but flax fiber has a high heating value.

FUEL BURN MODEL CHECK

Due to the fact that the use phase is very influential to the final results the calculations were double-checked in order to assure validity. Logical reasoning was used to understand the results.

First of all, we know that the saved fuel per flight (Δm_f) is 12,31kg. Based on this the saved carbon footprint per flight can be calculated $\Delta m_f * CF = 12,31*3,57 = 43,95 kgCO2eq$. In turn, the saved carbon footprint for 5 years of operation (so 2950,15 flights, Table 5.2), are $43,95 * 2950,15 =$ **129648 kgCO2eq**. Hence, this is a saved carbon footprint for the whole aircraft B787-8, for 5 years of operation. In other words, when composites in all 18 business class seats are changed from conventional to bio composites.

Logically speaking, that number should be the same as the difference between the carbon footprint in the use phase for 1 seat used for 5 years (Table 5.6) multiplied by 18 seats. The number in Table 5.6 is 7203 kgCO2eq; however, here the more accurate number is used which is 7202,64 kgCO2eq. The calculation is the following $7202,64 kgCO2eq * 18 seats =$ **129648 kgCO2eq**. Since the number is the same as in previous calculations, it can be concluded that the fuel burn model presented in the use phase is correct.

5.4.2. LCA conclusions and Recommendations

It can be seen from the LCA that bio composites are better for an environment than conventional composites made from glass fiber/phenolic composite when looking at total carbon footprint and energy requirement. In particular, the emissions in one business class seat for 5 years of operation are reduced by 7205kgCO2eq (-38%) and 107605MJ (-38%). However, water usage is bigger for bio composite by 1330 litres (+47%), which is an issue further discussed in chapter 8. Additionally, it was found that the carbon footprint/energy requirement from the use phase contributes to more than 99% of total value from all the life cycle stages.

Looking at the LCA results it is recommended for aviation companies to start considering bio composite as the replacement for conventional materials. For now, bio composites are mostly exchanged for glass fiber composites. However, there is a potential to replace also aluminium parts which idea is confirmed by the experts (Interviewees 2, 3, 4, 6, 7, 8, 9, 10, and 12). In such a case another assessment should be conducted in order to determine whether bio composites have the potential to be lighter than aluminium parts. Probably such a replacement would require part re-designing (Interviewees 2, 4, 6, 8, 9 and 12). It is important to notice that bio composites are not better than conventional composites in all life cycle phases; however, when looking at the whole life cycle perspective are significantly better for an environment. Additionally, when considering any bio composites for the aviation industry, manufacturers should pay attention to whether the new material is lighter than the existing one. This is because weight reduction is essential for aerospace materials since the use phase impacts the total life cycle of the product by more than 99%. In case when a material is environmentally friendly in the manufacturing and disposal stage, when is heavier the benefits will be offset.

5

5.5. LCA Tool Evaluation

The LCA method serves as a method for the environmental impact assessment from the whole life cycle of a product. The beneficial aspect of this method is the fact that it is a standardized method; therefore, it sets the practices that should be followed in order to create good analysis. It is a clear method; however, it becomes very complex when going into details. In addition to that, many environmental data is not accessible. Especially, when one wants to gather primary data, so direct measurements, LCA exercise might take years until is completed. Hence, it is common to gather secondary data from available databases. However, good environmental databases such as Ecoinvent are not freely available; moreover, are very costly. The same accounts for good environmental software which are able to calculate many environmental impacts. Therefore, these are limitations that every researcher who is doing LCA struggles with. Hence, everyone is making many assumptions in a way, due to again, the complexity and lack of data. As a result, LCAs might be prone to biases and adjusted in a way the researcher wants to, despite mentioned standards. This is why, stating all the assumptions and limitations of an LCA is the crucial step as it allows for third-party evaluation. The mentioned limitation about biases is confirmed by the expert in transport policies (Interviewee 11). However, in the upcoming years, he/she predicts that LCAs will be carried out by an independent organization and not by the companies themselves. This is due to the fact that the company's LCA "will be completely biased" (Interviewee 11).

To sum up, the LCA method has its benefits and limitations; however, it is the most widely used method for environmental assessment and its popularity is only growing. Therefore, it is essential to realize its limitations when either creating or evaluating existing LCA. For this exercise, the LCA method was convenient as it might have been easily adjusted according to the LCA goal. Here, the adjustment was made to assess carbon footprint, energy requirement and water usage for which data was freely available for the researcher and to conduct a comparison between two materials without the necessity to develop a full product environmental assessment.

6

THE ECONOMIC ASSESSMENT

This chapter aims to develop an economic assessment of the chosen bio composite material using the framework of the Cost-Benefit Analysis (CBA) method. This tool has been chosen because as it was discussed in the Literature Study (chapter 2), CBA is suitable for determining whether a considered project should or should not be taken (Hoogmartens *et al.*, 2014). This is the case of this research. The goal is to determine the financial costs and benefits for the **decision-maker - an airline**, which assesses whether to buy business class seats produced with bio composite or conventional materials. It is worth mentioning that in the case of products going to aircraft, an Original Equipment Manufacturer (OEM), such as Airbus or Boeing, pre-selects products for their cabin by putting these in a catalogue, from which the final decision belongs to an airline. The bio composite business class seat assessed in the previous chapter is lighter; therefore, it is predicted that using it reduces fuel burn during aircraft operation. This chapter is developed by using information from chapter 5, such as saved fuel and saved carbon footprint when lighter bio composites are used in all the 18 business class seats in Boeing 787-8, for 5 years of operation.

The chapter presents the method that can help in the decision-making process on whether to buy bio composite business class seats. It is done by using the CBA framework and the reasoning that the project is worth doing when the present value of benefits exceeds the present value of costs. The objective of the CBA is to evaluate whether it can be profitable for airlines to buy products made from bio-based material, and in turn, whether developing them by manufacturers such as Collins Aerospace might bring value to the company. That is why the chosen in this study approach shows the costs and benefits from the customer (airline) perspective which is buying products from Collins Aerospace. The result of this analysis shows what would need to be the maximum price difference between conventional and bio business class seats in order to equal benefits from saved fuel during 5 years of operation.

Lastly, the conclusion is made about what is the difference between the financial CBA (fCBA) and social CBA (sCBA). The first one (fCBA) considers only financial benefits for airlines which stem from the fact that an airline saves on fuel and carbon taxes when having, lighter than conventional, bio seat. The second one (sCBA) includes the intangible benefits for society aroused from reduced pollution from the whole life cycle of the bio seat which is calculated in LCA (chapter 5). sCBA is calculated using the environmental prices from de Bruyn *et al.*, 2018. The names of fCBA and sCBA will be further used and the evaluation of LCA and CBA tools integration is further discussed in 8.

6.1. Framework of CBA

The goal of this CBA is to establish whether using bio composite seats can be financially beneficial for airlines, which are here the decision-makers. Therefore, the objective is to find what would need to be the maximum price difference between conventional and bio business class seat in order to equal benefits from saved fuel during 5 years of operation. That value is further called x. In order to find x the decision rule used in CBAs is applied (Boardman *et al.*, 2017):

$$\text{PV of Benefits} > \text{PV of Costs}$$

This CBA takes into account financial benefits from saved fuel, saved carbon fees, and saved environmental costs. This is done partially by using data from LCA in chapter 5. In particular, the benefits from saved fuel are based on calculations from the fuel burn model in chapter 5. Moreover, in LCA the calculated environmental impacts were carbon footprint, and inputs such as energy consumption, and water usage. Here, the financial benefits from saved carbon fees are using solely calculated carbon footprint. The savings from lower energy requirements and the burden from higher water usage are not included in the CBA. This is because, higher water usage and lower energy consumption from raw material extraction and manufacturing phase are included in the price of a material, and in turn, in the price of the final product which is unknown x. Next, the maintenance and disposal cost for both composite materials is assumed to be the same. Hence, the focus here is on the use phase where an airline can benefit from using lighter materials.

In addition, two CBAs are developed. One is purely economic - fCBA - where only tangible financial benefits are calculated which are fuel-saving costs and savings on carbon tax applied by the government. According to Hoogmartens *et al.*, 2014, fCBA "is a tool for private profitability assessment". Second is altruistic - sCBA - where in addition to purely economic benefits the societal value is added which is the reduced carbon footprint (Hoogmartens *et al.*, 2014). The two CBAs are considered for the EU zone, which needs to be specified because of the differences in carbon fees in different countries/regions. However, the comparison of the final value for different regions is carried out in the sensitivity analysis in section 6.5. The summary of the framework design is presented in Table 6.1.

Table 6.1.: fCBA and sCBA nomenclature

	fCBA	sCBA
Flights to, from and within **Europe**	x_1	x_2

Lastly, the two CBAs are calculated for the period of 5 years, where seats are bought in 2025 by an airline and used in years between 2026-2030. These years have been chosen after the technology analysis presented in chapter 4. In particular, the interview data showed that the prognosis for the commercial aviation market introduction of bio composites is for years between 2024-2027.

6.2. Identification of Costs and Benefits

In this section costs and benefits are identified where an airline has a standing. In other words, an airline's costs and benefits from choosing a bio composite seat instead of a conventional seat are included and counted.

6.2.1. Costs

In the case of both fCBA and sCBA, there is solely one cost which is the *18x*, where 18 stands for 18 business class seats in Boeing 787-8. The made assumption here is that an airline makes the same decision on all the 18 business class seats in their aircraft B787-8. Since x is the maximum price difference between conventional and bio business class seats it includes a few costs - x constituents - that contribute to the higher price of bio composite seat. The ones that are assumed are presented in Table 6.2 and should be also considered when looking at the final value of x resulting from this analysis. However, as in any new product development, there are many uncertainties when it comes to the associated costs; therefore, these are only the predicted ones by the thesis author. The assumption of x constituents does not impact the results of the CBA.

Table 6.2.: The constituents contributing to the predicted higher price of bio composite

Nr	x Constituent
1	Difference in price between conventional and bio composite materials
2	Difference in new product development costs
3	Difference in certifications costs

6.2.2. Benefits

As mentioned before, fCBA considers purely financial benefits such as fuel cost saving and carbon tax saving. On the other side, sCBA is the altruistic case where societal benefits from cleaner air are included. The summary of the considered benefits is presented in Table 6.3. These are predicted to be financial benefits because, in the previous chapter 5, it was calculated that when using bio seats, the fuel saving in one flight is 12,31 kg.

Table 6.3.: Considered benefits for fCBA and sCBA

	fCBA	**sCBA**
Benefits	Saved Fuel Cost (BF)	Saved Fuel Cost (BF)
	Saved Carbon Fees (BC)	Saved Carbon Fees (BC)
		Saved Environmental Costs (BE)

In addition to these, a benefit which could be also considered is improved customer relationship with an airline resulting in an increased number of passengers choosing a more sustainable airline. However, modelling such a benefit for the next years is out of the scope of this research and is something to consider in future research.

6.3. Economic Valuation of Benefits

The economic valuation of solely benefits is presented in this thesis, as the cost is what the research looks for. All the prices and cost savings are calculated using real values of €$_{2023}$ which was recommended by the associate professor from TU Delft, an expert in Cost-Benefit Analyses. Therefore, the prices are not discounted. The description of the used methods for each benefit valuation is presented in the following subsections.

6.3.1. SAVED FUEL COST

Using historical data on fuel prices for the past 5 years, the statistical analysis was developed - linear regression. The prices were taken from "Jet Fuel Daily Price", 2023, where the first month given was April 2018, and the last data on price is from March 2023 (60 months in total). The price changes with the trend line are presented in Figure 6.1. The detailed fuel prices for each month are presented in Appendix H in Table H.1.

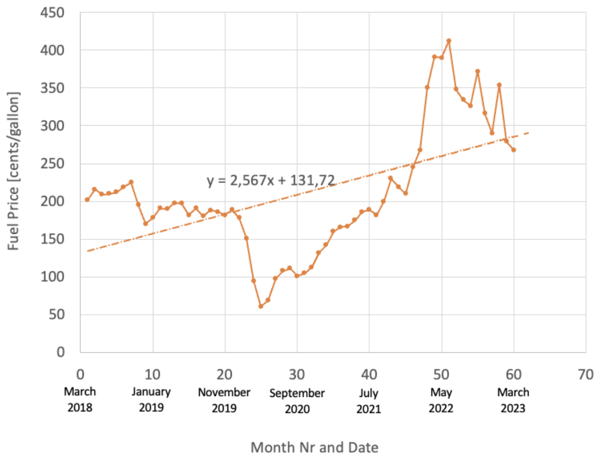

Figure 6.1.: Fuel prices for last 5 years. Own elaboration based on data from "Jet Fuel Daily Price", 2023.

The function for the linear trend is:

$$y' = 2,567x' + 131,72 \tag{6.1}$$

where:

- x' is the month number,
- y' is the price in cents/US gallon.

Further, the function 6.1 is used for the fuel price predictions. The month number for each year was taken by using the reference from function 6.1 that month 0 is March 2018. In addition, the month number for the whole year is set by looking at the January price. Lastly, three scenarios were created - low, baseline, and high. The low scenario is when future prices are lower by 10% than the predicted baseline scenario calculated using the function 6.1. The high scenario is for prices higher by 10% than predicted in linear regression. As a result, the following price prediction was created, where further only the benefits from the years 2026-2030 will be considered.

Using the fuel prices from Table 6.4 the saved fuel cost was calculated following the standard cost of fuel equations used in Collins Aerospace (personal communication with Collins Aerospace employee, 12 May 2023). Since the fuel price is different for each year, the saved fuel cost was calculated separately for each year, and next the results for 5 years (2026-2030) were added to each other. Therefore, the saved fuel from the fuel burn model

Table 6.4.: Estimated future fuel prices (PF) for years 2023-2030, in $\$_{2023}$

	Months	58	70	82	94	106	118	130	142
	Years	*2023*	*2024*	*2025*	***2026***	***2027***	***2028***	***2029***	***2030***
Fuel Price [cents/gallon]	Low	252,5	280,3	308,0	335,7	363,4	391,2	418,9	446,6
	Baseline	280,6	311,4	342,2	373,0	403,8	434,6	465,4	496,2
	High	308,7	342,6	376,4	410,3	444,2	478,1	512,0	545,9

developed in chapter 5 was used. From Table 5.3 it can be seen that that saved fuel weight per flight is $\Delta m_{f_{flight}} = 12,31kg$. Next, the number of flights in one year (N_{f1}) is calculated using data from Table 5.2 - $N_{f1} = N_{f5}/T = 2950,15/5 = 590,03$ flights per year. Therefore, the saved fuel in one year is $\Delta m_{f_{1year}} = \Delta m_f * N_{f1} = 12,31kg * 590,03 = 7263,26kg$. Using that value, the benefit from saved fuel cost (BF) can be calculated based on the equation:

$$BF = \Delta m_{f_{1year}}[kg] * PF\left[\frac{cents}{gal}\right] * \frac{\$}{cents} * \frac{gal}{L} * \frac{1}{\rho}\left[\frac{L}{kg}\right] * \frac{€}{\$} \tag{6.2}$$

where:

- PF - is the price of fuel from Table 6.4 for a particular scenario in a particular year,
- $\frac{gal}{L} = 0,264172$ - is the unit conversion from US gallons to Litres,
- $\frac{€}{\$} = 0,92$ - is the currency conversion for the current date of the research (20.05.2023)
- $\rho = 0,8\frac{kg}{L}$ - is the average Jet Fuel A density used by Collins Aerospace

For instance, for year 2026 in baseline scenario ($FP = 373\frac{cents}{gallon}$) the calculation looks the following:

$$BF_{2026_{baseline}} = 7263,26 * 373 * \frac{1}{100} * 0,264172 * \frac{1}{0,8} * 0,92 = €_{2023}8230,9 \tag{6.3}$$

The same methodology was applied for all the years and scenarios, the results are presented in section 6.4.

6.3.2. SAVED CARBON FEES

When it comes to carbon tax or carbon fees the research discovered that there is a difference in the value between countries or regions. For instance, European Union included aviation in the EU ETS (EU Emissions Trading System) where according to EU, 2022a, from 2026 airlines would need to fully pay for their carbon footprint by buying tradable allowances - EU Carbon Permits - which currently are traded for around €90 per tonne of CO2 emissions (ECONOMICS, 2022). The scheme includes all the flights to, from, and within EU (Scheelhaase *et al.*, 2018). On the other side, ICAO (International Civil Aviation Organization) introduced CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) which is an offset program and is voluntary for countries from the whole world until 2027. Here the tradable certificates - carbon credits - give the permit to emit one tonne of CO2 and mirror a CO2 reduction elsewhere (Scheelhaase *et al.*, 2018). There is no set price, since the transacted offsets are voluntary; however, based on available historical data, the mid-price scenario is around $3 for a tonne of CO2 emission (ICAO, 2022). Lastly, the USA is also debating on carbon taxes, and different bills were proposed. For instance, according to the Whitehouse Bill carbon tax should begin at $55 in 2020 and increase 5% annually (Whitehouse, 2022) to meet sustainability goals. Therefore, as can be seen, the carbon tax is highly variable when it comes to the place the aircraft is flying and is not very established yet. That is why, in this thesis the **focus is solely on the EU zone**; however, the sensitivity analysis presented further in the section 6.5 shows the results when CBA is developed using carbon fees applied in CORSIA trading scheme and carbon taxes suggested by the Whitehouse Bill.

The EU ETS, the trading scheme implemented in Europe was set to be gradually introduced. Aviation is included from 2012, and "airlines are required to monitor, report and verify their emissions and to surrender allowances against those emissions" (EU, 2022b). These allowances have been in majority given for free to airlines; however, the amount of free allowances is gradually decreasing since 2012. Consequently, from 2026 the free allowances will be phased out (EU, 2022a). Therefore, for calculations in this thesis it is assumed that from 2026, so from the year the CBA is done, airlines will pay the full amount of EU Carbon Permits. Currently (May 24, 2023), as being said the allowances are traded for €90 per tonne of CO2 emissions (ECONOMICS, 2022). However, this price is highly volatile and hard to predict for the future. Therefore, the literature was looked into. In particular, the forecast based on a survey done by IETA (International Emissions Trading Association) with PwC was used (IETA & PwC, 2022). 214 IETA members filled in the survey where they were asked, inter alia, about the expected carbon prices separately for the years 2022-25 and 2026-30. The result was that for 2022-25 the predicted value was €85,45 and for 2026-30 it was €99,63. These values were used as baseline values for further calculations. In addition, low and high scenarios were created, with -10% for low scenario and +10% for high scenario when compared to the baseline value. Hence, the final carbon prices (PC) are presented in Table 6.5.

Table 6.5.: Estimated future carbon prices (PC) for years 2023-2030, based on IETA and PwC, 2022, in $€_{2023}$

	Years	*2023*	*2024*	*2025*	***2026***	***2027***	***2028***	***2029***	***2030***
Carbon Price [€/tonne of CO2]	Low	76,9	76,9	76,9	89,7	89,7	89,7	89,7	89,7
	Baseline	85,5	85,5	85,5	99,6	99,6	99,6	99,6	99,6
	High	94,0	94,0	94,0	109,6	109,6	109,6	109,6	109,6

The prices from Table 6.5 are further used for calculating benefits from saved carbon fees. This is done using the methodology suggested by Collins Aerospace. First, the saved carbon footprint for each year of aircraft operation needed to be calculated. From chapter 5 the saving in carbon footprint in the use phase can be taken (Table 5.6). Hence, it is 7203kgCO2eq, which is saved when bio composites are used instead of conventional composites for one business class seat for 5 years. Using that value, the saved carbon footprint for all 18 seats (whole aircraft) for 1 year can be calculated. It is $7203 kgCO2eq * 18 seats/5 years = 25929,52 kgCO2eq$. To calculate the financial benefit from saved carbon fees (BC), this number (25929,52kgCO2eq) is further multiplied by the price of carbon (PC), translated from tonnes to kg. For instance, for the year 2026 in the baseline scenario ($PC = 99,6 \frac{€}{\text{tonne of CO2}}$) the calculation and result are the following.

$$BC_{2026_{baseline}} = \frac{25929,52 * 99,6}{1000} = €_{2023} 2583,4 \tag{6.4}$$

6.3.3. SAVED ENVIRONMENTAL COST

The environmental prices were taken from de Bruyn *et al.*, 2018 which were monetized based on a combination of damage and abatement cost. The research of de Bruyn *et al.*, 2018 presented three different scenarios using the value of $€_{2015}$. For this research, their values were translated to $€_{2023}$ values using the historical inflation rate between 2015 and 2023, taken from Webster, 2023 (for the date of 24/05/2023). To calculate the future environmental prices, the annual increase price of 3.5% was used as suggested by de Bruyn *et al.*, 2018. The final environmental prices are as presented in Table 6.6.

Table 6.6.: Estimated future environmental prices (PE), for years 2023-2030, based on de Bruyn *et al.*, 2018, in $€_{2023}$

	Years	*2015*	...	*2023*	*2024*	*2025*	***2026***	***2027***	***2028***	***2029***	***2030***
Carbon Footprint	Low	0,022		0,026	0,027	0,028	0,029	0,030	0,031	0,032	0,034
Environmental Price	Baseline	0,057		0,069	0,071	0,073	0,076	0,078	0,081	0,084	0,087
($€_{2023}$/kgCO2eq)	High	0,094		0,113	0,117	0,121	0,125	0,129	0,134	0,139	0,143

Using these prices the cost benefit from saved emissions is further calculated. To do so, the emissions from all the life cycle phases instead of the use phase are summed. The use phase is excluded because there is already a carbon tax applied, which is the price for carbon footprint from flying an aircraft, so the use phase. This is because, the associate professor of TU Delft, an expert in Cost-Benefit Analyses, said that including the use phase in the environmental costs would be a double-counting. Looking at the results from LCA in chapter 5 the difference in carbon footprint between conventional and bio composite is presented in Table 5.6. When subtracting the use phase from the final score the difference when using bio instead of conventional composites in carbon footprint for one business class seat per 5 years is $-7204,87 kgCO2eq - (-7202,64 kgCO2eq) = -2,23 kgCO2qe$. Therefore, the saving in carbon footprint for 18 business class seats, in 1 year is $\frac{2,23 kgCO2eq * N_s}{T} = \frac{2,23 kgCO2eq * 18 seats}{5 years} = 8,02 kgCO2eq$. To calculate the benefit from the saved environmental cost, this number (8,02kgCO2eq) was multiplied by the environmental price (PE) for a particular year and in a particular scenario from Table 6.6. For instance, for the year 2026 in the baseline scenario ($PE = 0,076 \frac{€}{kgCO2eq}$) the calculation and result are the following.

$$BE_{2026_{baseline}} = 8,02 * 0,076 = €_{2023} 0,608 \tag{6.5}$$

As can be seen, the saved environmental cost is low, because of the exclusion of the use phase, which is included in carbon tax calculations. However, in the case when similar calculations are developed for a country that does not have carbon tax implemented (and an airline is not paying it voluntarily), the use phase should be included in sCBA in saved environmental cost. Also, when LCA would include different environmental impacts (e.g., ozone depletion), these values should be calculated in environmental costs. This is because carbon fees cover solely carbon footprint.

6.4. COMPARISON OF COSTS AND BENEFITS

This section presents the final values for the developed CBAs using the prices and equations described in the section above. It is divided into fCBA and sCBA, where values only for baseline are shown. Using the dependence that Benefits > Costs the value of x_1 can be found. The final values of x for low and high scenarios are presented here in ± values, while detailed numbers are shown in Appendix H.2.

6.4.1. FCBA

The financial Cost-Benefit Analysis for years 2026-2030 in the EU zone (under EU ETS) is presented in Table 6.7. The included benefits are only from savings on fuel costs and carbon fees. Social benefits from greener products are not included, these are considered in the following subsection.

Table 6.7.: fCBA for flights under EU ETS trading scheme

	2025 Year 0	*2026 Year 1*	*2027 Year 3*	*2028 Year 3*	*2029 Year 4*	*2030 Year 5*	*TOTAL from 2025-2030*
Costs							
More expensive bio business class seat (x) * 18 seats	-18x_1						
Benefits							
Saved Fuel Costs €$_{2023}$		8231	8911	9590	10270	10950	
Saved Carbon Fees €$_{2023}$		2583	2583	2583	2583	2583	
Cumulative Costs	-18x_1						-18x_1
Cumulative Benefits		10814	11494	12174	12853	13533	60868

$$\text{Benefits} > \text{Costs} = 60868 > 18x_1 \Rightarrow x_1 < \frac{60868}{18} = €3381,57 \pm 338,16$$

Therefore, the conclusion is that as long as the new business class seat with bio composites costs up to €3382 (baseline scenario) it is more profitable for an airline to buy it and use it for 5 years. That is the case when flights to, from, and within the EU are considered.

6.4.2. SCBA

The environmental Cost-Benefit Analysis for years 2026-2030 in the EU zone (under EU ETS) is presented in Table 6.8. In addition to the financial benefits, the environmental benefits such as smaller damage from air emissions which impacts society are included. Such environmental prices are called in the literature "shadow prices" as they are not directly observable in any market (Boardman *et al.*, 2017). These include the social costs of various pollutants. In addition, as mentioned before, since the carbon footprint from the use phase is already included in carbon prices, that phase of the life cycle is excluded here to avoid double-counting. Using the dependence that Benefits > Costs the value of x_2 can be found.

$$\text{Benefits} > \text{Costs} = 60872 > 18x_2 \Rightarrow x_2 < \frac{60889}{18} = €3381,75 \pm 338,27$$

Therefore, when including lower environmental impacts and translating these into monetary values, it can be seen that as long as the new business class seat with bio composites costs up to €3382 (baseline scenario) it is more profitable for an airline to buy it and

Table 6.8.: sCBA for flight under EU ETS trading scheme

	2025 Year 0	*2026 Year 1*	*2027 Year 3*	*2028 Year 3*	*2029 Year 4*	*2030 Year 5*	*TOTAL from 2025-2030*
Costs							
More expensive bio business class seat (x) * 18 seats	-18x_2						
Benefits							
Saved Fuel Costs €$_{2023}$		8231	8911	9590	10270	10950	
Saved Carbon Fees €$_{2023}$		2583	2583	2583	2583	2583	
Saved Environmental Costs €$_{2023}$		1	1	1	1	1	
Cumulative Costs	-18x_2						-18x_2
Cumulative Benefits		10815	11495	12174	12854	13534	60872

use it for 5 years. Hence, when comparing x_1 with x_2 the value of x_1 is €0,181 lower than the value of x_2 which in percentage difference is 0.005% lower. This stems from the fact that the use phase is contributing 99% to the whole life cycle emissions; therefore, excluding these results in a very low difference between x_1 and x_2.

In the case when an airline is operating in a country that does not have carbon fees implemented, the use phase in sCBA should be included. Such a case was tested in this study. In particular, the carbon fee was set to 0 in both fCBA and sCBA, moreover, in sCBA the use phase was included in the valuation of environmental benefits. The result was that x'_2 is by €586 bigger than x'_1, which in percentage difference is 22%. The details are presented in Appendix H.2 in Tables H.4 (for fCBA) and H.5 (for sCBA).

6.4.3. MARKET POTENTIAL ANALYSIS

Since the results from sCBA and fCBA are very similar, solely fCBA will be further considered. The values of x presented above were compared to the actual market prices and the price difference in solely material costs was estimated based on the information from industry experts. The prices of composites discussed in this section are summarized in Table 6.9.

Table 6.9.: Prices of materials

	Description of value	**Value [€]**	**Source**
a_1	Price of $1m^2$ of conventional composite	125 [1]	Collins Aerospace employee
$a_2 = a_1 * S$	Price of $S = 4,522m^2$ of conventional composite [2]	565	Own Calculations
$b_1 = a_1 * 3$	Price of $1m^2$ of bio composite	375 [3]	Interviewee 3
$b_2 = b_1 * S$	Price of $S = 4,522m^2$ of bio composite [2]	1696	Own Calculations
$= b_2 - a_2$	Difference in price of $S = 4,522m^2$	1131	Own Calculations

[1] The price for a typical panel dimension of 60x96 inches was given to be $500 and translated to $1m^2$.
[2] $S = 4,522m^2$ is the surface of all conventional composites in one business class seat, taken from chapter 5. The same S is used for bio composites
[3] The price of bio composites was estimated to be 3 times more expensive than the price of conventional composite. Information was given by the expert of Lufthansa Technik who said that their bio composite material is 3-4 times more expensive than conventional composite (Interviewee 3). For these calculations, 3 times more expensive bio composite is considered since the expert expects a decrease in the future price.

In Table 6.9 it can be seen that the bio composite materials are more expensive by €1131. Going back to the Table 6.2 where the x constituents were pointed out, the following calculations can be done, as presented in Table 6.10.

Table 6.10.: Analysis of market potential by calculating x constituents

Nr	x Constituent	Value [€]
1	Difference in price between conventional and bio composite materials	1131 [1]
2	Difference in new product development costs	not known
3	Difference in certifications costs	not known
	Value of x_1 (as calculated in section 6.4.1)	3382 ± 338
	Remaining value of x_1 (= x_1 − Nr 1 x Constituent)	2251 ± 338

[1] Taken from calculations presented in Table 6.9

It is predicted that the remaining value of x_1 includes also the difference in new product development costs and the difference in certifications costs which are not known and probably can be calculated solely after the product is already introduced. The development and certification of a new product with bio composites might be more expensive; however, prices of bio materials might also go down. Therefore, it can be concluded that it is possible to achieve the product price below x_1 by Collins Aerospace; hence, the bio business class seat is more profitable for an airline.

6.5. SENSITIVITY ANALYSIS

6

Values discussed above are predicted values, as are based on certain assumptions. Therefore, to handle the analysis uncertainties the sensitivity test is usually conducted (Boardman *et al.*, 2017). Here, the sensitivity analysis is conducted for solely fCBA due to the fact that as proved before the difference between fCBA and sCBA is negligible for the EU zone. The purpose of the sensitivity analysis is to compare the original scenario to the case when an airline is flying in a different region than the EU zone; therefore, different carbon taxes apply. Hence, the three additional cases of fCBA were chosen and are presented in Table 6.11, where here the equivalent value to unknown x is y introduced to avoid confusion between values. Therefore, y is the maximum price difference between conventional and bio business class seat set to equal benefits from saved fuel during 5 years of operation. It is calculated for the three mentioned cases presented in Table 6.11.

Table 6.11.: The cases of fCBA for sensitivity analysis

Case Nr	Carbon Fee Case	Unknown value
1	CORSIA Offset Program	y_1
2	Whitehouse Bill	y_2
3	No carbon fee applied	y_3
Original	*EU ETS Trading Scheme*	x_1

CORSIA is the case for global aviation. The carbon fees for that case were taken from ICAO, 2022, where the data was given for 2021. The low scenario is $\$_{2021}1{,}19$, baseline scenario is $\$_{2021}3{,}08$ and high scenario is $\$_{2021}20{,}67$. These numbers were translated to $€_{2023}$ and future values were raised by 9,5% annually, as predicted in ICAO, 2022.

The Whitehouse Bill is an example of the US case. The carbon fees were taken from Whitehouse, 2022 where $\$_{2020}55$ was given with an annual increase of 5%. The value was translated to €$_{2023}$, the low scenario was assumed to be with a future annual increase of 4% and the high scenario with 6%.

The results in the final value are presented in Figure 6.2. The detailed numbers of cases 1, 2, 3, and the original case are presented in Appendix H.2 in Tables H.6, H.7, H.8 and H.2, respectively. In Figure 6.2 it can be seen that the final price difference varies between €2398 and €3720 for different cases and scenarios. For the baseline scenario, the differences between the original case and sensitivity cases are presented in Table 6.12. As predicted, the biggest difference, as -21% is when no carbon fee is applied and solely saved fuel cost is calculated. When CORSIA's carbon fees are considered, the final value of y is 20% lower than x_1 for EU ETS carbon fees. Lastly, Whitehouse Bill's carbon fee reduces the final value of x_1 by only 3%.

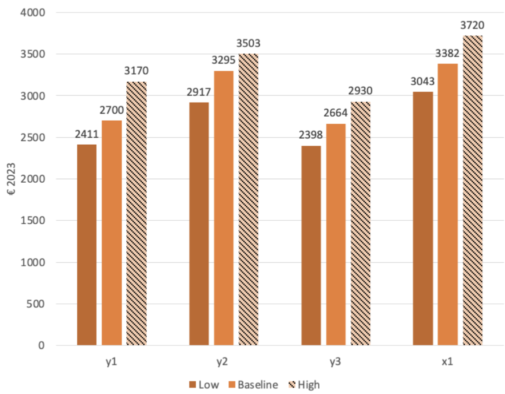

Figure 6.2.: Results from sensitivity analysis for three different cases with three scenarios

Table 6.12.: Values for different carbon fee cases, with comparison to original case in baseline scenario

	Value [€$_{2023}$]	Value difference between a case and original case in **baseline scenario** [€$_{2023}$]	Percentage difference between a case and original case in **baseline scenario** [%]
x_1	3382 ± 338	-	-
y_1	2700^{+470}_{-288}	-682	-20%
y_2	3295^{+207}_{-378}	-86	-3%
y_3	2664 ± 266	-718	-21%

6.6. CONCLUSION AND RECOMMENDATION

Conducted Cost-Benefit Analysis concluded that since seat with bio composite materials is lighter, in all the investigated cases an airline will benefit financially from having bio seats instead of conventional seats. The result is that one bio composite seat can be more expensive up to x =€3382±338 to be still profitable for an airline. This is the price difference for the case of flight to, from and within the EU, since the carbon tax regulations are different for other regions. It was also calculated that in current material market prices, there is real potential in achieving that price. In particular, the material costs for the bio composite seat are predicted to be more expensive by €1131 when compared to conventional composite seat. Since €1131 can be included in x, the remaining value is €2251 which can be used for other expenses associated with bio product development. Therefore, it is concluded that using bio composite materials can be profitable for airlines; hence, there might be demand for such a product. Additionally, the sensitivity analysis was conducted for different regions where it was concluded that in the "worst-case scenario", when a country/region does not apply any carbon fees, the price difference between bio and conventional seat would be reduced by 21%; hence, to the value of €2664±266. In real life, the mix of EU and outside EU flights is the case. Therefore, the actual price by which a bio composite seat can be more expensive is probably somewhere between €3382±338 and €2664±266. Hence, the widest range by taking unfavourably the high and low scenarios is €2398 - €3720.

Looking at the results, the recommendation is that seat of Collins Aerospace which is made from innovative bio composites have a potential to find clients; therefore, should be considered to be developed. Such business class seat would be not only more environmentally friendly but also financially profitable for airlines.

6

6.7. CBA TOOL EVALUATION

In this research, the CBA method was suitable to discover variable x which is unknown, and to estimate whether it might be profitable for airlines to buy bio composite seat instead of conventional. Additionally, both CBAs used information from LCA results. In particular, fCBA took the numbers from the fuel burn model developed to calculate the difference in the use phase carbon footprint. sCBA used the calculated difference in emissions from all the other life cycle stages and integrated it into monetized values. The details on tools integration, its challenges and opportunities is presented in chapter 9.

The problem which was approached when integrating tools was to whether include the use phase saved emissions in saved environmental costs since these were already taken into account when calculating savings from carbon fees. It was suggested by the academic expert to not include it because it would cause double-counting. Additionally, discounting was another problem. The fuel, carbon, and environmental prices given by external sources, presented also the annual price increase. It was not clear whether this prediction includes future inflation or not. Therefore, again the academic expert in CBAs (associate professor of TU Delft) was asked for an opinion and said that these predictions include inflation. Additionally, he/she suggested calculating all the financial benefits in $€_{2023}$ to avoid additional uncertainty on discount rates.

To sum up, the CBA method is good for both, purely financial considerations and also altruistic valuation when not only financial benefits are considered. Therefore, it is also a suitable method to develop the research further by including also benefits from better brand image and customer sustainment which is predicted since sustainability has currently a big value in the aviation industry.

7
RESULTS

The results presented in this chapter cover the results from the case study. In particular, the conclusions from the bio composite analysis, environmental assessment and economic assessment of the innovation are presented below.

7.1. RESULTS FROM BIO COMPOSITE ANALYSIS

The analysis of the investigated sustainable innovation - bio composite material for aircraft interiors was developed in chapter 4. Based on interviews, literature, personal communication and direct observation data collection methods, the technology was analysed and the results were used in further study. First, the drivers were identified using the institutional theory. The recognized pressures are coercive, normative and mimetic which are from governmental regulations, intrinsic motivation for sustainable solutions, and competitors' developments, respectively. Additionally, two important reasons for technology development were presented - environmental and economic reason. The potential of environmental and economic benefits were found, but the need to validate that for the specific case of bio composite in aircraft interiors was recognized. With that insight the further analysis in chapters 5 and 6 of environmental and economic benefits was justified. Also, the two main challenges associated with the technology were found - (1) lack of consistency in mechanical properties which vary between places of planting/seasons, and (2) flammability of natural fibers. The first challenge is still an issue; however, the second was already overcome by a few European companies. That insight showed that flammability requirements are very strict in the regulations of aircraft interiors; therefore, for further analysis the example of the chosen material needed to be from already developed material that meets these very specific requirements. Therefore, the next step of bio composite investigation was the pattern of development analysis where the main innovations in the aviation and automotive industry were plotted on the framework's timeline. The result of that research was that the technology is highly developed in the automotive industry; however, in the aviation industry, it is still an emerging topic. In particular, three companies were identified that developed suitable bio composites for aircraft interiors; however, until very recently had no demand for their product. Additionally, the experts expect the first introduction of that material in commercial aviation between 2024-2027, while the large-scale production in 2033-2038. These discoveries were pieces of evidence of how particular is the aviation industry and confirmed the impression from challenges analysis, that not every bio composite that is suitable for the automotive industry would be suitable for aviation. With that insight, further analysis covered a comparison of different materials that can be used in bio composites to determine the good combination. The result was that the material which was developed by an EU project (Cayley) was found, which meets the mechanical properties, flammability requirements and is indicated by the research of Vidal *et al.*, 2018 to be the most environmentally friendly. Hence, this part resulted in the chosen material which is further a subject for sustainability assessment. In particular, the comparison is developed between conventional (aramid fiber paper honeycomb core with glass fiber/phenolic resin skins, coated with DecaBDE flame-retardant) and bio composite (polyetherimide foam core with flax fiber/geopolymer resin skins, coated with non-halogenated flame-retardant).

7.2. RESULTS FROM THE ENVIRONMENTAL ASSESSMENT

The environmental assessment in chapter 5 used the Life Cycle Assessment tool to calculate the carbon footprint, energy consumption and water usage for all the life cycle stages of two composites. The study shows that using bio composite materials in aircraft interiors can bring environmental benefits because of lower carbon footprint and lower energy consumption in the whole life cycle. In particular, when replacing conventional composite with bio in one business class seat for 5 years of its usage in an aircraft, a 38% reduction in both carbon footprint and energy consumption is calculated. This equals the reduction of 7205 kgCO2eq and 107605 MJ. With an assumption that an aircraft has 18 business class seats, the reduction equals 129688 kgCO2eq and 1936884 MJ for 5 years of operation. However, the research also shows that the water usage for bio composites is 47% higher than for conventional composites. This stems from the fact that the production of natural fibers requires more water when the plants are grown. The 47% increase results in the additional usage of 1330 litres of water for one business class seat and 23932 litres for 18 seats. In addition to that, the research showed that in the whole life cycle the use phase, so when the seat is flying and its weight is responsible for fuel burn and in turn for emissions, accounts for more than 99% of carbon footprint and energy consumption in the whole life cycle. This confirms the statement in the literature that the new material which is used needs to be lighter than the current one to reduce the carbon footprint of the product. Regarding water usage, 93% is consumed during the raw material extraction phase as predicted. Next, it was found that bio composite materials are not better for the environment in all the life cycle phases. In particular, the increased carbon footprint was in manufacturing (+29%), maintenance (+6%) and disposal phase (+54%). However, the reduced carbon footprint was for the raw material extraction phase (-69%), transportation phase (-31%) and use phase (-38%). The pattern was the same for energy consumption with slightly different percentage numbers. On the other side, water usage was higher for bio composites in every phase of the life cycle where was present.

7.3. RESULTS FROM THE ECONOMIC ASSESSMENT

When it comes to economic assessment from chapter 6, the methodology of the Cost-Benefit Analysis was used to help in the decision-making process, where the decision-maker is an airline assessing whether to buy 18 business class seats which use bio composite materials or to stay with conventional materials. The study treated the difference in price between conventional and bio seats as variable *x* and developed CBA for airlines operating to, from and within the EU (under the EU ETS trading scheme). The financial benefits were saved fuel costs, saved carbon fees and saved environmental costs. The region needed to be specified, due to the fact that in different countries/regions, different regulations on carbon tax apply. The result was that a business class seat which uses bio composites can be €3382±338 more expensive and having it by an airline for 5 years of operation would be still more profitable. By comparing that number to the current market prices of materials it was concluded that it is possible to achieve such a price. In addition to the financial CBA, the social aspects were added; hence the second, social CBA was developed. In particular, it was calculated how the CBA's result changes when the saved environmental costs are included, which are the saved costs from a smaller burden for people's health. The result showed that including these is negligible for the final score. This is because the use phase reduced emissions were already included in the benefit of a saved carbon fee; therefore, to avoid double-counting in social CBA only the emissions from other than the use phase life cycle stages were taken into account. Since the use phase is the most influential when it comes to emissions, the difference in results was minor. Lastly, the sensitivity analysis investigated the cases for different regions, where different carbon tax regulations are predicted to be applied. For the global case under CORSIA regulation, the price difference between conventional and bio composite seats would need to be 20% lower, for the US case (under Whitehouse Bill carbon fee) 3% lower, and for the case with no applied carbon tax, it would need to be 21% lower. These differences from the original scenario stem from the fact that carbon fees under EU ETS regulation are the highest. Hence, using these it can be concluded that for different cases of carbon fees and various price scenarios, the searched value by which bio composites can be more expensive is between €2398-€3720.

7.4. SUMMARY

To sum up, the analysis showed that bio composites are a good solution for aircraft interiors from both environmental and economic point of view. This is because their usage reduces significantly carbon footprint and energy consumption. However, it is important to realize that bio composites use significantly more water, which is the negative side of bio composites and is further discussed in chapter 8. From an economic perspective, the lower weight of bio composites results in lower costs of operations for airlines which contributes to savings during the business class seat lifetime. The values presented in this research are for the seat lifetime of 5 years, which is a rather pessimistic scenario. Therefore, in case the real life of such a seat is longer than 5 years, the carbon footprint reduction and financial benefits would be only bigger.

8
Discussion

8.1. General Discussion

The aviation industry is changing and sustainability pressures are the source of these changes. Some can say that sustainability is a fad of current times. However, in the case of the aviation industry, the new incoming regulations, carbon footprint limits, and carbon taxes are not making it a fad anymore. The goals for emissions reduction are set by the highest governing parties and are very precisely indicating where the industry will be going. Therefore, aviation companies should be aware of incoming changes and invest in sustainable solutions. The time to do so is now. As it is stated by Qiu *et al.*, 2021, currently, green innovations in the aviation industry are becoming essential in sustainable development and a better future. Moreover, this thesis by the framework of institutional theory concluded on the existence of coercive, normative and mimetic pressures which are from the government, intrinsic motivations and competitors, respectively. These pressures on sustainable innovations accelerate new developments; therefore, sooner or later the competitors will be coming up with greener solutions. Hence, to sustain a competitive advantage, Collins Aerospace should take the lead in these industry changes.

In the case study presented in this thesis, the bio composite material as sustainable innovation was chosen. The presented methodologies were applied for the comparison of particular bio and conventional composites material. The lower weight of bio composite materials presented by a few researchers such as Duflou *et al.*, 2014; Henschel, 2019; Le Duigou and Baley, 2014; Vidal *et al.*, 2018 indicated that the environmental and economic benefit might be associated with this technology, which needed to be validated for the case of using it in aircraft interior business class seats. Since the specific material for calculation was needed, the bio material - geopolymer panel - was chosen because of the data availability and indicated environmental potential by Vidal *et al.*, 2018. This thesis is not suggesting that this is the best and only material that can be used in aircraft interiors. It only gives an example of the possible material where the suggestion is based on the material developed in an EU project. The case study proves that it is possible to achieve better environmental and financial scores when using geopolymer panels in aircraft seats. It confirms the predictions and statements on bio composites in the literature such as Bachmann *et al.*, 2017; Le Duigou and Baley, 2014; Vidal *et al.*, 2018. The calculated in this thesis environmental benefits of this particular material are similar, as only 7% higher in carbon footprint, to the ones presented by the research of Vidal *et al.*, 2018 which described the material for the first time. Additionally, the case of bio composites shows that using these in aircraft interiors reduces carbon footprint and energy requirement; however, it increases water usage. The same results were achieved by Gomez-Campos *et al.*, 2021. Weiss *et al.*, 2012 also stated that bio composites are not better than conventional materials in all impact categories. However, when it comes to water consumption, Weiss *et al.*, 2012 mentioned that because water consumption is dependent highly on the region in which the plants are grown, the authors excluded it from research as that impact was difficult to quantify. Nevertheless, the water usage issue should be kept in mind when making decisions on implementing bio composites. When plants are grown in countries where water scarcity is not an issue, that should not be an obstacle to bio products development. However, when higher water usage is a problem, different sustainable, but not natural fibers, can be considered such as recycled carbon fiber studied, inter alia, by Bachmann *et al.*, 2017.

The sustainability assessment also shows that aviation companies by the development of lightweight innovations can also make their products profitable for their customers. Therefore, it confirms the statement argued in Ekins and Vanner, 2007 that sustainability assessment can help businesses to monitor and manage sustainable usage of natural resources and to create economic value. It is a win-win situation, when Collins Aerospace has demand for their product while acting responsibly, and airlines are willing to have a sustainable product not only because of environmental benefits but also because it is profitable for them. Therefore, by creating a product that is both eco-friendly and profitable for airlines, the manufacturer is implicitly "forcing" the customers to be sustainable. This is the change that needs to occur now in the aviation industry and for which the decision-making should be focused. Additionally, it is important to stress that the cost of aircraft operation is increasing. For instance, already in 2026 airlines will need to pay the full price of carbon permits for the flight to, from and within the EU (EU, 2022a). Therefore, any reduction in their carbon footprint will be highly appreciated and the demand for sustainable innovation is going to only rise. In addition, Sustainable Aviation Fuel (SAF) is predicted to be introduced since it is pushed by regulations. However, the price of SAF will be rather higher than the price of current jet fuel as recently stated by the CEO of Boeing in the article of Bushey *et al.*, 2023. Therefore, the benefits from saved fuel will be only higher. In addition, carbon fees as presented in this thesis will also be rising (ICAO, 2022; IETA & PwC, 2022; Whitehouse, 2022). All of these lead to the situation where airlines would be willing to pay more for products which allow them to have financial benefits when operating an aircraft. Therefore, since the demand for sustainable solutions will be only growing, to recognise the potential of an innovation the sustainability assessment as presented in that research is necessary and can help in guiding decisions in an organization. Hence, the fact that literature of Bond *et al.*, 2012; Buytaert *et al.*, 2011; Myllyviita *et al.*, 2017; Waas *et al.*, 2014 presented sustainability assessment as a process supporting decision-making is confirmed by this research. However, in addition to that, this study emphasizes that before conducting the sustainability assessment, the market analysis which includes drivers, challenges, and the stage of development should be done in order to understand market dynamics and technology potentials. The institutional theory, introduced by DiMaggio and Powell, 1983, is relevant for drivers' assessment of any sustainable innovation for the aviation industry because the identified pressures are concerning the whole industry.

Additionally, the presented integration of LCA and CBA is discussed as a suitable connection which can broaden the perspective in the decision-making process. That is supported by Dong *et al.*, 2018 which said that the results from LCA can give valuable information to support tools for decision analysis such as CBA. This research confirms that by showing that the fuel burn model from the use phase of LCA is used in fCBA and sCBA, while environmental impacts from other life cycle phases are used in sCBA (Figure 9.1). However, the presented here LCA and CBA combination for the sustainability assessment of specifically an aircraft product was not found in the literature; therefore, the methodology needed to be explored. As mentioned in the Literature Study in chapter 2, some of the reviewed researches concluded on issues of LCA and CBA combination; hence, these are further evaluated in the context of this research. Hoogmartens *et al.*, 2014 said that LCA evaluates the whole life cycle while CBA only the duration of the project. Here, that was not an issue because the whole life cycle was equal to the duration of the project and both were 5 years. Therefore, as long as the researcher matches these two, that challenge can be overcome. Next, Dong *et al.*, 2018 mentioned that the focuses of the studies are different, LCA is centred on a product while CBA is on a project. While this is true, that does not need to be a problem since the product manufacturing, its usage and disposal can be treated in LCA as a product development but in CBA as a project. This is because innovation is more than a product and can be organized as a project which can be seen in the work of Verganti, 1997. Additionally, Dong *et al.*, 2018 said that geographical boundaries might be difficult to be matched in LCA and CBA. However, this research shows that as long as these are clearly indicated and scenarios for different regions are provided, the two tools can be still combined. Creating different cases for other regions can also be valuable. Hence, not fully matching the geographical boundaries of the two methods is not an obstacle and combining these can still provide guidance for the decision-making process. To sum up, the issues indicated in the literature are relevant; however, as presented in this thesis, can be omitted; hence the integration of LCA and CBA tools brings opportunities for more informed decision-making.

Looking at the case study results, the decision after this sustainability assessment would be to invest in this material development. However, that conclusion cannot be generalized to all bio composites or to all sustainable innovations. In some cases it may happen that bio composite which is consisting of different sub-materials is heavier than conventional material; therefore, it might lead to bigger environmental burdens and financial costs on fuel. This is exactly the case in the research of Gomez-Campos *et al.*, 2021. Also, for different sustainable innovations, the results might be not that positive. For instance, when an innovative aircraft microwave is being considered, which uses less energy but is heavier, the LCA and CBA results might be worse despite improved performance, and airlines might not be willing to buy such a product. Further, the results of sustainability assessment cannot be easily predicted. Hence, for any material or product, a separate analysis needs to be developed to properly support decision-making where the presented in the thesis methodology can be used. Moreover, developing both the environmental and economic assessment together can help the producer, of any sustainable innovation for aircraft, to predict the lack of demand before the investment in development is made. As described by Hockerts and Wüstenhagen, 2010, sustainable innovation is when the exploitation of economic opportunities occurs which helps to achieve social and environmental benefits. Hence, their definition of sustainable innovation presents it as a technology that is both environmentally and economically beneficial. The sustainability assessment can help with confirming or rejecting that.

The methodology presented in this thesis for sustainability assessment is suitable for products/technologies/innovations used in aircraft and for comparative purposes, as it is based on differential numbers. Thus, it is the comparison of old and new products that shows the direction a company should pursue. Moreover, as mentioned, it can be also used for different sustainable innovations in the aviation industry. For instance, the assessment of biofuel for aircraft also called Sustainable Aviation Fuel (SAF) should also cover both analyses - the environmental and economic/social. In the literature, Møller *et al.*, 2014 combined LCA and CBA when assessing biofuel introduction in the sector of Danish road transport. Hence, such analysis for the aviation sector should be also possible. Moreover, this thesis shows that is it advantageous when the sustainability assessment is preceded by the analysis of the market, drivers, challenges and the current stage of the technology. When that and sustainability assessment is developed the full picture can be seen and a complete analysis can be done. In this example, the environmental assessment of comparing jet fuel to SAF would be similar, since the same life cycle phases are considered. Only different data would need to be collected. In economic assessment, the cost would be again, the unknown price difference, and in benefits, the lower carbon fees would need to be included which according to regulations apply to SAF.

Lastly, the research was designed in a way that qualitative methods such as interviews, literature study, personal communication and direct observation were used as inputs for a quantitative study in which environmental impacts (LCA) and financial benefits (CBA) were calculated. In particular, the most important inputs from the qualitative study were that the environmental and economic potential of bio composites in aircraft interior products might exist but there is no complete agreement on that matter within literature and interviewed experts. Hence, the qualitative analysis showed that to confirm or reject that, it is essential to develop a sustainability assessment (especially environmental and economic assessments) in this research. Additionally, qualitative methods presented that the material chosen for LCA and CBA calculations should be the one already developed and designed to be used in aircraft interiors which passed the flammability requirements of the aviation industry. Without proper qualitative research, a different material example could have been chosen for a quantitative study, which could have appeared to be not suitable for aircraft interiors. Moreover, the quantitative methods gave an answer about the potential of the technology which is an important insight for Collins Aerospace. Therefore, it can be summarized that qualitative and quantitative amalgam supported proper decision-making during the project and ensured more reliable results which responded to the needs of the company.

8.2. LIMITATIONS

Along with positive results, the study has also limitations which need to be acknowledged. Most of the limitations stem from the assumptions that were taken on the way, especially in LCA. Therefore, these are in more extensive detail explained in chapter 5 in section 5.1. Here, the most important for the whole work limitations are pointed out.

To begin, the sustainability assessment focuses on the environmental and economic assessments; however, it has limited scope regarding the social aspect which is the third pillar of sustainability. In this work, solely the social implications of reduced carbon footprint are considered in the economic assessment part. However, a deeper social analysis should be developed of the effects on aspects such as level of employment in a region or noise level. These were mainly limited because of low data availability.

The next limitation is that in the LCA the environmental impacts were limited to carbon footprint, energy consumption and water usage, while in non-fast-tracked LCAs also other impacts should be covered such as toxicity, land use, acidification, ozone depletion etc. The reason for limiting this study in that area concerns the limited resources. In particular, it was because of the lack of not freely available Ecoinvent database which has data on other than the carbon footprint environmental impacts. Following that, data on carbon footprint, energy requirement and water usage were taken from the Granta EduPack database which is also using estimated from models values. Therefore, presented environmental impacts depending on the region or manufacturer can be in reality different. Also, the data on the chosen bio composite is from other research and the weight of particular sub-materials could not have been validated.

Another limitation is the fuel burn model, which covers only the cruise phase of the flight. Hence, take-off, landing, and taxiing are not included. However, the simplified model is enough to recognize the minimum saved fuel weight, as when missing phases would be included the saved fuel weight would be even more significant than presented in this thesis. Next, the jet fuel price prediction is based on linear regression statistical analysis which is a simplified method. Prediction of jet fuel prices would require a lot of additional research which was out of the scope of this thesis.

Lastly, there is a limitation concerning the chosen research method - the case study. Due to the fact that the case study investigates a specific bio composite (geopolymer panel) the concluded environmental and economic potential might be specific solely to the chosen case. As mentioned before in section 8.1, the results from LCA and CBA of this case study cannot be generalized to all bio composites or further to all sustainable innovations. This is because every sustainable innovation has different specifications, and the sustainability assessment needs to be conducted separately for each of them. However, the methodology for conducting such a sustainability assessment as presented in the case study is possible to be generalizable to other sustainable innovations in the aviation industry. In order to minimize the limitation concerning the chosen research method, all the research steps were clearly described in order to enable different researchers to follow the methodology when conducting an exercise for different technologies.

8.3. Future Research

There are many ways the research could be developed further. The most recommended would be to extend the work by adding more aspects of social assessment such as job creation or reduction, change in living standards, change in the level of noise etc. Then, the presented sustainability assessment would be more comprehensive. Also, it would be advised to extend the current environmental analysis by adding more detailed data and including more environmental impacts from the Ecoinvent database. Additionally, for such an exercise usage of the LCA software would be suggested. When different environmental impacts are taken into account it might happen that a sustainable technology reduces carbon footprint; however, it causes bigger ozone depletion. Therefore, considering these might give more environmental information to the researcher on an innovation. Also, similar work using the same methodologies on different sustainable innovations in the aviation industry would be beneficial, as it might give more insights into what should be added to make the methodology more generalizable. Next, in the economic assessment, an addition of future situations when SAF is used would be also valuable, as it might give an insight into what would be the cost of flying in the future. Following that, a more developed fuel price model could be done, to more accurately predict future costs. Lastly, the addition of other benefits to the Cost-Benefit Analysis might be also a valuable indication. In particular, how the sustainable product in aircraft cabins influences customer satisfaction, customer sustainment, airline brand etc. Additionally, for Collins Aerospace these benefits could also be considered, as when being the first-mover in making the products from bio composites, the brand image is also positively impacted.

8.4. LINK TO MANAGEMENT OF TECHNOLOGY

The Master's Thesis describes how the management of technology can be done in the company and is linked to the scientific topic of sustainability assessment. It is a scientific study in a technological context, where technology, strategy and product development management come together. Additionally, the described methodology is based on the knowledge from the MoT curriculum. In particular, on how to analyse an innovation, how to responsibly manage technology and how to do a financial analysis, everything from a corporate perspective. For instance, the utilized institutional theory which was used for technology drivers identification was taught in Technology, Strategy and Entrepreneurship class. CBA analysis was presented in the Financial Management course. The analysis of technological development pattern was in-depth taught in the Emerging and Breakthrough Innovations class. All of these were combined to support the decision-making process involving many stakeholders and different interests, which is the approach taught in other classes of MoT.

When it comes to my personal feedback on the study program, the taken courses from the MoT program helped me in many parts of this thesis. Firstly, almost all the courses included writing a scientific paper; therefore, it help me in getting used to the style and requirements of academic writing. Next, the importance of looking at the problem using a transdisciplinary approach taught me always to consider stakeholders, their different interests, and to look at the problem from different angles. Also, very valuable for this thesis is the importance that the MoT program puts on responsible innovation, sustainability and innovativeness. I believe that these are imperatives of current times, and I am happy that MoT courses taught me that approach. A great addition to MoT would be more courses which are directly working with companies such as the Integration Moment course. I believe that working with professionals shows students how to cooperate in an organization's environment. To sum up, the taken courses and the approach of the professors were great, I always felt listened and my questions and answers were always valued. I believe that this empowers students and helps them in their future careers. I am very grateful for everything that the MoT program taught me.

9 CONCLUSION

The final chapter first presents the general conclusions from the research, where the defined in the Introduction (chapter 1) problems are referred to. Next, the answers to the research questions are given. Lastly, the recommendations for the scholars and the company are stated.

9.1. GENERAL CONCLUSIONS

The research presents the methodology for the sustainability assessment of sustainable innovation in the aviation industry. It shows that the sustainability assessment tools can help in the decision-making process regarding investment in sustainable innovation. This is because by complex analysis organizations are able to evaluate the environmental impacts of the new product and to determine whether its development is economically viable. Having these assessments shows whether the development of innovation is environmentally responsible and if it brings economic value to customers and the organization itself.

The thesis answers the academic and industry problem. The **academic problem** because the sustainability assessment tools are tested in the case study on how these can help in the decision-making process. In particular, tools such as LCA and CBA are used where their integration is presented and evaluated. Available literature points out the challenges but also opportunities of such tools combination and these are examined in the case study and further commented on in the answers to the research questions presented in the next section. Also, the methodology for the sustainability assessment of the products for aircraft is developed, which can be also used for different sustainable innovations. Additionally, the attempt to analyse an innovation using theoretical frameworks is made and it is concluded that such an analysis gives valuable insights for the assessment; therefore, should be developed before performing the sustainability assessment task. The **industry problem** is answered by the case study itself. As mentioned in the problem statement, Collins Aerospace company is eager to invest in sustainable solutions for aircraft interiors. Therefore, the assessment of bio composites is developed and it shows the potential of the technology giving valuable information for future decision-making regarding the development of products made from bio materials. In particular, the research shows that using bio composites in aircraft business class seats reduces the carbon footprint in the whole life cycle of the product and can be economically attractive for customers (airlines) as it saves their operational costs. The product is predicted to be financially viable for airlines even when bio composite seats will be more expensive. This is because the cost savings from the lower weight of the product, and in turn, lower fuel burn are determined to be significant.

9.2. ANSWERS TO RESEARCH QUESTIONS

First, the **main research question** is answered which is *"How can the integrated sustainability assessment tools support the decision-making process regarding the development of a sustainable innovation for the aviation industry?"*. The answer that the research brings is the following. The sustainability assessment where both environmental and economic analyses are conducted in detail can together help in the decision-making process. The aviation companies such as Collins Aerospace by careful technology investigation as presented in this thesis can confirm or reject investment in sustainable innovation. Here, the chosen tool for environmental assessment is the Life Cycle Assessment (LCA) and for economic assessment the Cost-Benefit Analysis (CBA), which are commonly used tools and can be integrated for sustainability assessment. It is concluded that combining both tools for the assessment of aircraft products is a suitable choice, especially in the case when the costs of new products are not fully known, but the benefits can be calculated. Additionally, adding LCA results to CBA calculations can support making informed decision towards sustainable development and responsible innovation. Based on the study, it can be concluded that environmental assessment can help in the decision-making process in a way that the companies producing products for aircraft can act responsibly and invest in products that are predicted to have a lower carbon footprint and better environmental impact. In addition to that, economic assessment can assist as well and deliver information on whether a new, more sustainable product would find clients focused on mainly financial profits. In other words, whether airlines would be willing to buy such a product from a financial perspective. Therefore, when these two methods are used together as presented in the study, the bigger picture can be seen, which gives direction in the decision-making process. Hence, any organization after both assessments can see whether their responsible actions will have a chance to get attention from the market. Later, by the development of such products companies can implicitly "force" the customers to be sustainable. For instance, this is the case when results from the environmental assessment are positive and the economic assessment suggests that customers might be financially interested in the solution. Hence, sustainability assessment informs an organization that by developing such technology they create a sustainable product which is competitive on the market.

9

The next conclusion is the answer to the first research sub-question: *"How can the innovation theoretical frameworks provide insights for the sustainability assessment of bio composite technology?"*. The investigation of the market and current state of technology with its drivers and challenges indicates where further analysis should be focused on. In the case of bio composites, firstly, the identified drivers showed the institutional pressures from the government, intrinsic motivation and competitors (coercive, normative and mimetic pressures respectively). The indicated by the experts and literature reasons for the technology development are the environmental and economic potentials of innovation. Hence, that analysis based on theoretical frameworks proved the need for further validation of mentioned environmental and economic benefits. This is also because the statements of experts and literature were not always consistent. Therefore, such analysis justifies further the decision on deeper analysis of the two pillars of sustainability - environmental and economic with the inclusion of societal benefits in the CBA. Additionally, identifying challenges concluded that the regulations in the aviation industry are the main problem. This was supported by the analysis of the technology development patterns which showed the discrepancies between the automotive and aviation industry, confirming that aviation regulations might be the main reason for that. Hence, the conclusion was made that the material for further assessments is the one which was already developed and meets the requirements. Additionally, the pattern of development analysis showed the prognosis for technology introduction which was needed for setting the economic assessment time frame. It concluded that in 1-4 years bio composites should be implemented in commercial aviation. In addition, the investigation of patterns of technological development helped in identifying existing prototypes of technology and placing them together in a timeline. Next, different prototypes could have been compared together using comparative analysis to determine the material for further sustainability assessment which in that case was chosen to be a geopolymer panel from the Cayley project. The study shows that before any investments, the market and technology analysis should be developed, which is the purpose of chapter 4. The theoretical frameworks from innovation studies served here as guidelines on how to do such an analysis; however, the task is possible to be adjusted or performed using different methods. The research proved that such analysis based on theoretical frameworks can give valuable information and inputs which can be used further in sustainability assessment.

The following research sub-question can be answered - *How can a Life Cycle Assessment (LCA) and Cost Benefit Analysis (CBA) be applied to assess the sustainability of a product for aircraft usage?* To begin, LCA and CBA sustainability assessment tools can be used separately or together, where the second is the case of this research. The tools give different information for the decision-making process. LCA shows environmental results such as carbon footprint from all the life cycle phases; however, CBA presents the economic results of a decision in monetary values. When using LCA for the assessment of the environmental impacts of a product for aircraft usage, an important aspect was found. The use phase of such a product has the biggest influence on environmental results from all the life cycle stages. In the case of bio composites, it contributed by more than 99% to the entire life cycle carbon footprint. This is because the product's weight contributes to the fuel burn of an aircraft, and in turn, to the emissions. That is why, it is essential to realize how important, for environmental results, is that product which is meant to be used in an aircraft is lightweight. This is not the case when LCA is developed for a regular product. For instance, a desk chair is an environmental burden during the raw material extraction, manufacturing, transportation, maintenance and disposal phase. However, not in the use phase. When it comes to CBA, two approaches were used in this research. One is the fCBA, which is solely the financial tool. The second one, sCBA, is an integrated tool which next to economic costs and benefits includes environmental impacts. The fCBA is using information from LCA's use phase where the fuel burn model is developed. This is to calculate the saved fuel weight (for the CBA's benefit of saved fuel cost) and saved carbon footprint (for the CBA's benefit of saved carbon fees). Hence, only one life cycle phase assessed in LCA is used further in CBA; however, the most influential one. When it comes to sCBA, in addition to what is included in fCBA it also monetizes the environmental impacts from all the other than the use phase life cycle stages. Hence, sCBA is using information from all the calculated LCA phases. The summary of how the two methods intercept and fill in each other is presented in Figure 9.1. Hence, looking at the figure, it can be seen that the most important link between LCA and both CBAs is the fuel burn model from the use phase of LCA; therefore, should be well-designed to give reliable results.

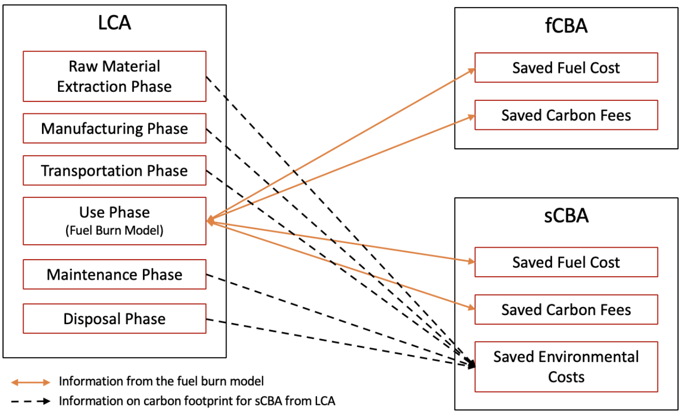

Figure 9.1.: Conclusion on LCA and CBA combination methodology for the assessment of sustainable innovation for aircraft

Next, the answer to the third research sub-question is concluded in the study - *What challenges and opportunities are associated with integrating LCA and CBA sustainability assessment tools?* When it comes to the approached challenges, the biggest problem was with the double-counting of the impacts from LCA in sCBA. This challenge was not stated in the searched literature; hence, is an issue that this study identified. The problem appeared because the carbon footprint from the use phase was applied to calculate the benefit from the saved carbon fees which is imposed by carbon tax regulations. Therefore, the issue was whether to include the carbon footprint from the use phase when calculating sCBA. Since non of the available literature presented a similar integrated sustainability assessment methodology for aircraft products, the answer to this issue could have not been found. Hence, the advice from an expert was to not include it in sCBA, to avoid double-counting. Therefore, in the case study, the results of LCA which could have been implemented in CBA were the carbon footprint from raw material extraction, manufacturing, transportation, maintenance and disposal phases (Figure 9.1). In such a situation, when the use phase was excluded, the effect of including the carbon footprint from LCA in CBA was negligible. This was because the use phase is the most influential phase on the LCA's results. However, in the case when LCA's calculated environmental impacts are not solely the carbon footprint, but also other impacts (such as ozone depletion, acidification, human toxicity etc.), the issue of double-counting would need to be rethought. This is because the carbon fee is solely on carbon footprint. Hence in sCBA, the other than carbon footprint impacts from the use phase would need to be included. When it comes to the advantages of integrating two methods, it is the fact that more information on innovation is given when not only environmental scores are known, but also economic value. Additionally, the two tools are complementary which can be seen in Figure 9.1. For instance, the developed fuel burn model in LCA is the same as for CBA; therefore, a significant part of the work for CBA is done in LCA. Also, the saved emissions in the use phase needed for calculating saved carbon fees in CBA are already calculated in LCA. Therefore, LCA gives a lot of important inputs for CBA, making the task of developing economic assessment easier and faster. These examples and conclusions support the statement that LCA can provide valuable information for CBA which was mentioned in the research of Dong *et al.*, 2018. Additionally, as discussed in chapter 8, the literature indicates the three main issues of LCA and CBA integration: (1) key focus (product vs. project) (Hoogmartens *et al.*, 2014), (2) life span and included life stages (Hoogmartens *et al.*, 2014), and (3) different geographical boundaries (Dong *et al.*, 2018). The first issue is overcome when the innovation process and product development are treated as a project, which is also a common approach in the literature. The second challenge is conquered when the assessed life span of LCA and CBA is equalled to each other (here are set to 5 years). Also, the considered life stages are the same when conducting sCBA as the emissions from other stages than the use phase are additionally included. Lastly, the third problem was considered the most relevant in this thesis; however, was mitigated by creating cases for the CBA calculations in different regions. Then the impact on results of chosen geographical boundaries in CBA can be realized and may also serve as valuable information for the decision-making process.

Lastly, the answer to the last research sub-question was investigated - *"What factors can impact the results from the sustainability assessment tools?"* The carried out research showed that factors such as (1) chosen geographical boundaries, (2) fuel burn model and (3) input data, can significantly impact the results of the sustainability assessment tools. To begin, it was found that chosen geographical boundaries can have a significant effect, especially on CBA's results. This is because regionally, different carbon tax regulations apply where the EU's carbon fees are globally the highest. For the case of bio composites, the higher carbon tax influenced higher benefits from saved carbon emissions. In the case study example, the final value changed up to 21% when CBA was conducted for the region where lower or no carbon tax is applied. Therefore, it can be concluded that since the aviation industry is highly global different scenarios for different regions should be considered in economic assessments as it has a significant impact on the results. Next, the chosen fuel burn model, which was in this research the fuel burn model, can change the results of LCA and CBA. As mentioned, the use phase contributes to 99% of the whole life cycle carbon footprint. Therefore, the model itself is crucial for the results of both CBA and LCA. When a different, more simplified model, is used, the saved fuel and emissions would be smaller. When a more advanced model with take-off, landing and taxiing is used, the LCA's emissions and CBA's financial benefits would be higher. Therefore, deliberate consideration of the used model, equations and boundaries of a model is necessary to show reliable results. Lastly, the input data has a significant impact on the results of a sustainability assessment. In the case of LCA, it was mainly the environmental input data, which has different values between databases or literature.

Hence, the decision of a database for secondary LCA data has an impact on the results. Also, in the case of CBA, the estimated future price of fuel and carbon fees can change the final values. That is why considering low, baseline and high prices scenarios is important when conducting CBA, as it shows the uncertainty of the results.

9.3. Contributions to existing research

There are a few contributions to existing research that this study brings. To begin, the research realized an approach for an extensive combination of qualitative and quantitative research methods. Such a combination allowed for obtaining a bigger picture, triangulating between literature and experts' statements, and validating obtained results from calculations. Additionally, it enabled an approach to the topic from various angles to bring value to the current knowledge and fill in the missing gaps.

Next, the study partially reproduces the research of Vidal *et al.*, 2018 which is conducting an LCA, inter alia, on the geopolymer panel. The same methodology is applied, but different environmental databases are used for the assessment of environmental impacts. The results from both LCAs are concluded to be similar.

In addition, the study utilizes insights from institutional theory and the evolutionary model of Ortt *et al.*, 2010. In other words, the theoretical approaches are applied in the analysis of a particular innovation. The study shows that the utilization of theoretical frameworks is supporting the decision-making process, as the analysis itself gives valuable insights into the technology. Therefore, the study argues that it is a good practice to analyze the technology using theoretical frameworks before realizing sustainability assessment. In particular, investigating pressures using institutional theory helps in realizing why there is a need for such innovation and how an organization can respond to that. Potentially in the future, regular analysis of existing pressures with the usage of institutional theory may help aviation companies in following the regulations and market needs in order to properly respond to these with innovative technologies. Also, concluding on the pattern of technological development helps in establishing the current market situation and creating a prognosis for the future. Moreover, using this theoretical framework might help aviation companies to understand how the analysed technology has evolved and to compare it to similar innovations in other industries. All the mentioned information assists in choosing the most environmentally and economically promising innovation to invest in and on which further sustainability assessment should be conducted.

Last but not least, the research tests the LCA and CBA integration and refers to the challenges and opportunities of such a combination described in the literature. Moreover, presents one more challenge which was approached; however, not presented in the literature, the double-counting. It also shows the detailed methodology for the tools' integration when assessing a product for an aircraft, summarized in Figure 9.1. The proposed methodology for sustainability assessment can be applied to different sustainable materials or innovations.

9.4. Recommendations

When it comes to the recommendations for scholars, the integration of the sustainability assessment tools - LCA and CBA - can bring challenges that are pointed out by the literature. However, these issues as presented here by proper research design can be overcome. To begin, it is recommended to start with LCA and then pursue further with fCBA or sCBA. This is because the information from the use phase of LCA can be used in both fCBA and sCBA, while other life cycle phases can be implemented in sCBA (Figure 9.1). When one wants to develop solely fCBA, without LCA, the creation of a fuel burn model would be necessary. Moreover, this combination is especially suggested when one wants to compare materials or innovations with each other. This is because in that case much unknown information can be disregarded, and the focus is on what is important for the researcher. From what this study taught when geographical boundaries do not match, different scenarios can be created. In this case, the spatial boundaries of LCA were mainly global, however, sometimes limited to particular regions. For instance, when it was known that manufacturing of conventional composite is done in the US. However, for CBA, the region needed to be the same for all the calculations as it indicates the carbon tax regulations. Therefore, since these did not match, the impact of choosing different regions on CBA's results is tested by creating different scenarios in the sensitivity analysis. Hence, it is suggested to consider creating scenarios for different regions when the geographical boundaries do not match to have information on how it impacts the results. Additionally, the combination of LCA and CBA was found to be suitable for product assessment, but it is advised to treat product development as a project. In other words, to act as the whole life cycle of the product is a project and assess in CBA all the life stages. In that situation, the time frame of LCA and CBA can be properly matched. On the other side, the opportunities for decision-making support given by the integration of the tools are promising. Therefore, it is recommended to assess not solely one pillar of sustainability but also to investigate others to have a better overview of the technology and its potential. Additionally, the research shows that sustainable solutions for aircraft will have high demand in the next years. Therefore, the scientific frameworks for the sustainability assessment of such innovations will be needed. This is because not all the technologies which are claimed to be eco-friendly are actually good for the environment. Hence, the LCAs for new solutions from independent scientists will be needed to validate the claims of the industry.

When it comes to the recommendation to the company, the usage of bio composites in aircraft interiors is suggested, as these can be beneficial from an environmental and economic point of view. Therefore, it is recommended to seriously consider innovative bio materials for future products. The detailed analysis presented in this thesis proves their potential. Additionally, for other investment decisions on sustainable innovations, using the presented methodology to conduct sustainability assessment would give valuable insights. This is because aviation companies are responsible for delivering more environmentally-friendly products; hence the environmental assessment gives an answer to whether the considered technology is actually better for the environment. Next, the companies also need to make profits. Therefore, to make sustainable innovation which is competitive in the market an economic assessment is necessary. It is important to say that the methodology presented here is suitable to be used for the comparison of different sustainable innovations that are meant to be used in operating aircraft. When developing such an assessment for another material, the main change would be the different data for the LCA input. However, the fuel burn and CBA benefits equations stay the same but use the new data. When one is not aiming in comparison, but in the sole assessment of a material or technology, the methodology would need to be adjusted, because now it is based on the differential numbers regarding saved fuel burn and saved emissions. Further, it is recommended to do such assessments for any product that is supposed to be used in an aircraft before the development stage begins. This is because, in the early stage of product development, the problems such as unnecessarily heavy parts or the usage of unsustainable materials can be identified and changed. The costs of such a change in the initial stage of development are low, but the benefits might be significant.

Moreover, it is advised to invest in sustainable solutions. The analysis of the sustainable technology - the bio composite material - showed that current sustainability pressures are not only the market fads. The framework of institutional theory pointed out the coercive, normative and mimetic pressures (chapter 4). The coercive pressures are because of new, incoming regulations regarding sustainability which will affect the whole aviation industry. For instance, when airlines will not reduce their carbon footprint their operational costs will significantly increase from 2026. That is why, the demand for sustainable solutions is there, and since the pace of innovations in the aviation industry is rather slow, companies should start as soon as possible to meet the demand. The normative pressures are from intrinsic motivation and values within an organization. These are visible not only in Collins Aerospace company but also in other aviation companies which are their customers and are demanding solutions which are better for the environment. Additionally, mimetic pressures are also driving the industry. This is because some aircraft product manufacturers are working on lightweight solutions and innovating in that field to meet the airline's demand; hence, the whole industry is pressured to follow that and also deliver lightweight and sustainable innovations. Looking at the mentioned pressures, additional two recommendations are pointed out. First, conducting the drivers' analysis based on the innovation literature stream helps in presenting pressures which might contribute to the organization's decision-making. Second, it is advised to invest in sustainable innovations because the presented discoveries identified under scientific rigour are a warning to aviation companies and point out the imperative of giving more attention to sustainability matters. Also, the mentioned pressures on sustainable solutions are predicted to accelerate the pace of sustainable innovations in the industry; therefore, from a business perspective, the company should start acting now to sustain competitive advantage. The last argument that shows the direction of aviation is the prediction that carbon tax in the EU and other regions will rather only increase. Therefore, the benefits from reduced emissions will be only higher in the future.

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A

Literature on Sustainable Innovations in the Aviation

Table A.1.: Sustainable innovations discussed in the literature

Subsystem	Innovation Field	Innovation	Number of papers where innovation mentioned
Propulsion Subsystem	Alternative fuels	**- Biofuels**	**12**
		- Hydrogen	5
	Novel engines	- Hybrid Solutions	1
		- Hybrid-electric distributed propulsion	1
		- Electric Engine	3
	Advancements in turboprop engines	- Propellers for high flying speeds	3
	Advancements in turbofan engines	**- Ultra-high bypass turbofans**	**7**
		- Increasing the peak pressure and temperature within the engine	1
		- Improving engine component efficiency	1
		- Engine monitoring and management	1
		- Intelligent engine control systems	1
Aerodynamic Subsystem	Aerodynamic elements	- Winglets	5
		- Airborne Equipment	1
	Improved design of wing	- High aspect ratio wings	3
		- Improved propulsion/airframe integration	1
		- Laminar wing profiles and advanced airframe design	1
Structural Subsystem	Capacity	- Better use of capacity	2
		- Ultra high capacity	1
	Materials	**- Lightweight materials**	**9**
		- Advanced materials for additive manufacturing	1
		- Lighter aircraft paint and coatings	2
Paradigm Shift	Airship		1
	Sky Car		1
	Blended wing bodies	- Canard wings	2
		- Flying 'v'	2
		- Double-bubble fuselage	2
	Alternative Powertrains		1
	Landing gearless aircraft		1

Table A.2.: Sustainable innovation in the literature

Nr	Reference	**Sustainable Innovations** (assignment of innovation to number in Table A.3)																											
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
1	Mousavi and Bossink, 2017	x																		x									
2	Pereira *et al.*, 2021	x				x							x																
3	Lee and Mo, 2011	x	x					x										x		x									
4	de Haan, 2007	x	x				x								x				x	x			x	x	x	x	x		
5	Kim *et al.*, 2019	x																											
6	Pinheiro Melo *et al.*, 2020	x	x			x														x								x	
7	Yan *et al.*, 2016	x											x																
8	Bows *et al.*, 2009	x	x				x	x					x		x		x												
9	Lee, 2010	x						x	x	x						x													
10	Teoh and Khoo, 2016							x												x									
11	Mrazova, 2013						x	x					x							x		x							
12	Qiu *et al.*, 2021	x											x	x	x			x		x		x							
13	Rohacs, 2022	x	x	x		x		x												x	x				x	x	x		x
14	Ranasinghe *et al.*, 2019				x			x			x	x								x									
15	McManners, 2016	x																											
	SUM	**12**	**5**	**1**	**1**	**3**	**3**	**7**	**1**	**1**	**1**	**1**	**5**	**1**	**3**	**1**	**1**	**2**	**1**	**9**	**1**	**2**	**1**	**1**	**2**	**2**	**2**	**1**	**1**

Table A.3.: Assignment of numbers to sustainable innovations

Nr	Sustainable Innovation
1	Biofuels
2	Hydrogen
3	Hybrid Solutions
4	Hybrid-electric distributed propulsion
5	Electric Engine
6	Propellers for high flying speeds
7	Ultra-high bypass turbofans
8	Increasing the peak pressure and temperature within the engine
9	Improving engine component efficiency
10	Engine monitoring and management
11	Intelligent engine control systems
12	Winglets
13	Airborne Equipment
14	High aspect ratio wings
15	Improved propulsion/airframe integration
16	Laminar wing profiles and advanced airframe design
17	Better use of capacity
18	Ultra high capacity
19	Composite materials
20	Advanced materials for additive manufacturing
21	Lighter aircraft paints and coatings
22	Airship
23	Sky Car
24	Canard wings
25	Flying ’v’
26	Double-bubble fuselage
27	Alternative Powertrains
28	Landing gearless aircraft

B

Literature Study on Bio Composites

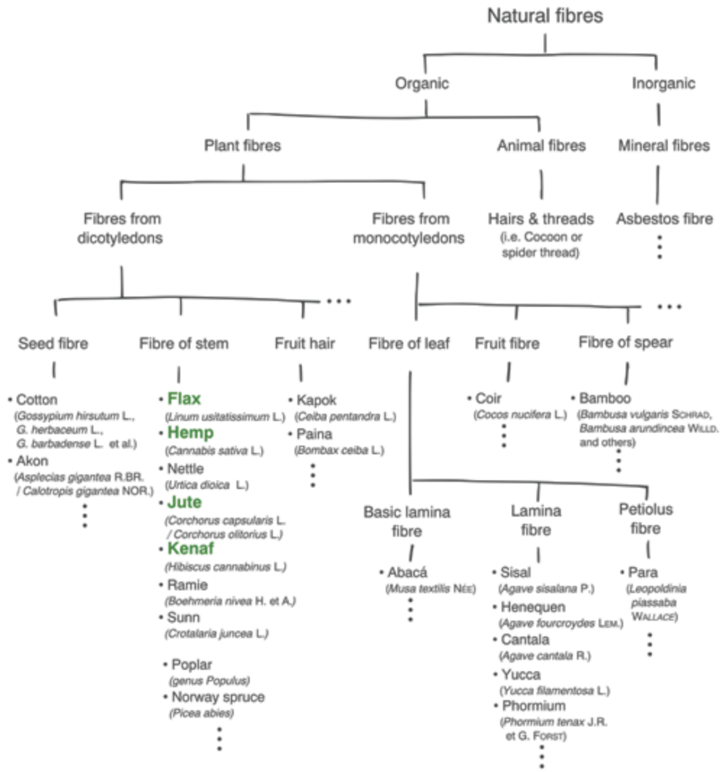

Figure B.1.: Overview of natural fibers. Source: Barth and Carus, 2015

C
INTERVIEWS

Table C.1.: List of interviewees

Interviewee Nr	Relevance	Company
1	Associate Professor, working with bio composites	TU Delft
2	Industry professional, working on FlaxPreg T-UD FR	EcoTechnilin
3	Industry professional, working on AeroFLAX Bio Composite	Lufthansa Technik
4	Associate professor, doing research on advanced aerospace materials and bio composites	TU Delft
5	Assistant professor, doing a research on sustainable design	TU Delft
6	Assistant professor, doing research on advanced aerospace materials and bio composites	TU Delft
7	Industry professional, advanced materials engineer	Collins Aerospace
8	Industry professional, working on ampliTex™ and powerRibs™ flax fiber reinforcements	Bcomp
9	Industry professional, Composites Engineering Manager	Collins Aerospace
10	Industry professional, Research Engineer in Materials Manufacturing	Collins Aerospace
11	Associate professor, doing research on transport policies	TU Delft
12	Industry professional, working on sustainable composites for aircraft	Collins Aerospace

C

Consent Form

You are being invited to participate in a Master Thesis research study titled "The Analysis of a Sustainable Innovation from Environmental and Economic Perspective: Case Study of Bio Composites in Aircraft Interiors". This study is being done by Agata Żarnowska from the TU Delft in collaboration with Collins Aerospace on an internship basis.

The purpose of this research study is to determine the methodology for environmental and economic assessment of a sustainable innovation in the aviation industry, with a focus on bio composites. The interview will take you approximately 15 minutes to complete. The audio recording will be collected, and later transcript will be done. A summary of the interview will be created. The data will be used in the final Master Thesis and the summary will be included in the thesis. The Master Thesis will be made publicly available once the study is completed, including the summary.

As with any data collection activity, the risk of a breach is always possible. To the best of our ability, your answers in this study will remain confidential. We will minimize any risks by making interviews anonymous, only the general position within the company will be noted down. The answers will be stored in the OneDrive of TU Delft which is only accessible by authorized individuals. The TU Delft project team will be only authorized to access the data of the interview.

Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any questions. After the Master Thesis submission, the detailed version of transcripts, and the audio recordings, will be archived for future research for up to 2 years in TU Delft under the supervision of the research team. The results will be published in the TU Delft repository and only the most important results will be presented in an anonymous form.

Contact details of the Corresponding Researcher:
Agata Żarnowska, e-mail: agata.zarnowska@collins.com/a.i.zarnowska@student.tudelft.nl

In case of any complaints contact Responsible Researcher:
Dr Jenny Lieu, e-mail: J.Lieu-1@tudelft.nl,
Dr Geerten van de Kaa, e-mail: g.vandekaa@tudelft.nl

To agree to the interview and to this Opening Statement, sign below.

Signatures

______________________	______________________	________
Name of participant [printed]	Signature	Date

I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

AGATA ŻARNOWSKA

______________________	______________________	________
Researcher name [printed]	Signature	Date

Study contact details for further information: Agata Żarnowska, +48602239679, agata.zarnowska@collins.com, a.i.zarnowska@student.tudelft.nl

Figure C.1.: Consent Form

D

COMPARISON OF BIO COMPOSITES

Table D.1.: The average values from Table D.2. Environmental impacts of fibers, resins and bio composites, per 1kg of material. Abbreviations: PFA - perfluoroalkoxy, PEI - polyetherimide, PP - polypropylene, EP - epoxy.

Investigated Material	**Average Carbon Footprint [kg CO2 eq]**	**Average Non-Renewable Energy Usage [MJ/kg]**	**Average Water Depletion [litre]**	**References**
		Fibers		
Flax fiber (only)	0,46	10,85	54,4	Barth and Carus, 2015; Duflou *et al.*, 2014; Gonzlez-Garca *et al.*, 2010; Joshi *et al.*, 2004; Le Duigou *et al.*, 2011; Shen and Patel, 2008, Granta EduPack
Hemp Fiber (only)	1,05	8,75	2600	Barth and Carus, 2015; Gonzlez-Garca *et al.*, 2010; La Rosa *et al.*, 2014; Shen and Patel, 2008, Granta EduPack
Jute Fiber (only)	1,26	38,6	2380	Barth and Carus, 2015, Granta EduPack
Kenaf Fiber (only)	1,06	174,00	1500	Barth and Carus, 2015, Granta EduPack
		Resins		
Bio-epoxy resin	4,08	1,90	-	La Rosa *et al.*, 2014
Epoxy resin	6,82	42,21	-	La Rosa *et al.*, 2014
PFA resin	2,1	-	-	Tumolva *et al.*, 2009
PEI	19,9	245	541	Granta EduPack
Phenolic resin	3,88	44,44	54,1	calculated based on Moliner Santisteve *et al.*, 2013, Granta EduPack
		Composites		
Flax/PP	31,05		188,70	Duflou *et al.*, 2014
Hemp/EP	5,7	89,00		Shen and Patel, 2008

Table D.2.: Full list of environmental impacts of bio composites or its constituents. Abbreviations: PFA - perfluoroalkoxy, PEI - polyetherimide, PP - polypropylene, EP - epoxy.

Investigated Material	Reference	GHG emissions [kgCO2eq]	Non-Renewable Energy Usage [MJ/kg]	Water Depletion [litre]	System Boundary	Comment
Flax Fiber (only)	Barth and Carus, 2015	0,80			Cradle-to-gate (not including carbon storage)	Comparison to glass fiber (2,2kgCO2eq)
	Le Duigou *et al.*, 2011	0,30	11,70		Cradle-to-gate (not including carbon storage)	Cradle-to-gate (not including carbon storage)
	Duflou *et al.*, 2014	0,34			Cradle-to-gate (not including carbon storage)	Cradle-to-gate (not including carbon storage)
	Gonzlez-Garca *et al.*, 2010	0,44	12,40		Cradle-to-gate	
	Shen and Patel, 2008		9,60		Cradle-to-gate	
	Granta EduPack	0,44	11,00	3300	Cradle-to-gate	
	Joshi *et al.*, 2004		9,55		Cradle-to-gate	
Flax/PP	Duflou *et al.*, 2014	29,90		206,5	Cradle-to-grave (automotive industry, here calculated. without EoL and use phases)	Flax mat-PP; Comparison to Glass mat-PP (39,2kgCO2eq, 288,5l); Equal stiffness/strength under bending
	Duflou *et al.*, 2014	32,20		170,9	Cradle-to-grave (automotive industry, here calculated. without EoL and use phases)	Short flax fiber-PP; Comparison to Glass mat-PP (37,7kgCO2eq, 244,7l); Equal stiffness/strength under tension
	Gonzlez-Garca *et al.*, 2010	0,44	12,40		Cradle-to-gate	
	Shen and Patel, 2008		9,60		Cradle-to-gate	Comparison to glass fiber (54,7MJ/kg)
	Granta EduPack	0,44	11,00		Cradle-to-gate	
	Joshi *et al.*, 2004		9,55		Cradle-to-gate	
Hemp Fiber (only)	Barth and Carus, 2015	0,84	5,00		Cradle-to-gate (not including carbon storage)	Mineral Fertilizer; Comparison to GF (35MJ/kg)
	Barth and Carus, 2015	0,68			Cradle-to-gate (not including carbon storage)	Organic Fertilizer
	Shen and Patel, 2008		6,80		Cradle-to-gate	Comparison to glass fiber (54,7MJ/kg)
	Gonzlez-Garca *et al.*, 2010	1,60	13,20		Cradle-to-gate	
	Granta EduPack	1,60	9,99	2600	Cradle-to-gate	Comparison to glass fiber (2,95kgCO2eq)
	La Rosa *et al.*, 2014	0,53			Cradle-to-gate	
Hemp/EP	Shen and Patel, 2008	5,70	89,00		Cradle-to-gate	Comparison to GF/EP (5,9kgCO2eq)
Jute Fiber (only)	Barth and Carus, 2015	0,77			Cradle-to-gate (not including carbon storage)	
	Van Dam and Bos, 2004	1,30	3,80		Cradle-to-gate (not including carbon storage)	
	Van Dam and Bos, 2004	1,90	8,00		Cradle-to-gate (not including carbon storage)	
	Granta EduPack	1,05	104	2380	Cradle-to-gate (not including carbon storage)	
Kenaf Fiber (only)	Barth and Carus, 2015	0,77			Cradle-to-gate (not including carbon storage)	
	Granta EduPack	1,35	174,00	1500	Cradle-to-gate	
Bio-epoxy Resin	La Rosa *et al.*, 2014	4,08	1,90		Cradle-to-gate	Comparison to petroleum based-epoxy resin (6,663kgCO2eq; 2,16MJ)
Epoxy Resin	La Rosa *et al.*, 2014	6,66	2,16		Cradle-to-gate	
	Bachmann *et al.*, 2017	6,97	92,25		Cradle-to-gate	
PFA Resin (Furan)	Tumolva *et al.*, 2009	2,1			Cradle-to-gate	
PEI foam	Granta EduPack	19,9	245	541	Cradle-to-gate	
Phenolic Resin	Moliner Santisteve *et al.*, 2013	5,8	8,37	-	Cradle-to-gate	
	Granta EduPack	1,96	80,5	54,4	Cradle-to-gate	

D

E

INVENTORY DATA

E.1. RAW MATERIAL EXTRACTION PHASE

Table E.1.: Inventory data for raw materials extraction phase, for 1 m^2 of panel

Material	**Weight [kg]**[1]	**Carbon Footprint [kgCO2eq], per 1kg of material produced**	**Energy [MJ], per 1kg of material produced**	**Water [l], per 1kg of material produced**	**Data source of environmental impacts**
CONVENTIONAL COMPOSITE PANEL - total weight of 1 m^2 is 2kg					
Aramid Fiber Paper	0,41	13,7[2]	270[2]	987[2]	Granta EduPack, Aramid fiber (Kevlar 149)
Phenolic Resin	0,42	1,96	80,5	54,4[2]	Granta EduPack, PF (casting resin)
Glass Fiber	0,73	3,14	54,3	99,2[2]	Granta EduPack, E-glass
DecaBDE	0,07	2,88[3]	26,75	-	Deng *et al.*, 2016
PVC film	0,37	2,9[2]	67,2[2]	200[2]	Granta EduPack, tpPVC
BIO COMPOSITE PANEL - total weight of 1 m^2 is 1,38kg					
PEI	0,09	19,9[2]	245[2]	541	Granta EduPack, Polyetherimide foam
Geopolymer Resin	0,6	0,0319 [2]	0,508[2]	14,4[2]	Granta EduPack, Kaolin (calcined)
Flax Fiber Yarn	0,22	0,46	11,6	3300	Granta EduPack, Flax fiber
Non halogenated	0,08	0,24 [4]	3,19	-	Deng *et al.*, 2016
PVC film	0,39	2,9[2]	67,2[2]	200[2]	Granta EduPack, tpPVC

[1] Taken from Vidal *et al.*, 2018
[2] Data noted in Granta EduPack as estimated
[3] Carbon footprint calculated using electricity data from Deng *et al.*, 2016 using US electricity mix (Appendix F)
[4] Carbon footprint calculated using electricity data from Deng *et al.*, 2016 using EU electricity mix (Appendix F)

E.2. MANUFACTURING PHASE

Table E.2.: Inventory data for manufacturing phase, for manufacturing of $1m^2$ of panel

Input/ Output	**Amount** [1]	**Carbon Footprint [kgCO2eq], per 1kg of material produced**	**Energy [MJ], per 1kg of material produced**	**Water [l], per 1kg of material produced**	**Data source of environmental impacts**
CONVENTIONAL COMPOSITE PANEL					
Electricity [MJ]	57,60	-	-	-	EU Electricity mix
Waste, Phenolic Resin [kg]	0,24	1,96	80,5	54,4	GrantaEduPack, PF (casting resin)
Waste, Hydraulic oil [kg]	0,00392	4,224	0,0308	-	Ekman and Börjesson, 2011 [2]
Wastewater [m3]	0,00000464	-	-	0,00000464	Vidal *et al.*, 2018
BIO COMPOSITE PANEL					
Electricity [MJ]	82,4	-	-	-	EU Electricity mix
Waste, Geopolymer Resin [kg]	0,08	0,0319	0,508	14,4	Granta EduPack, Kaolin (calcined)
Waste, Wood and cardboard [kg] [3]	0,00367	2,51 [4]	53,7 [4]	1790	Granta EduPack, Paper and cardboard
Waste, Garbage [kg]	0,00319	-	-	-	No data available as too broad
Waste, Flax fabric [kg]	0,00307	11,6	11,6	3300	Granta EduPack, Flax fiber

[1] Data source: Vidal *et al.*, 2018
[2] Type of hydraulic oil was not specified in Vidal *et al.*, 2018, therefore, the worst case scenario from Ekman and Börjesson, 2011 was chosen, the mineral-based hydraulic fluid
[3] Environmental data taken only for cardboard, as in Vidal *et al.*, 2018 it was not specified how much of either waste wood or waste cardboard is produced
[4] Carbon footprint/electricity from recycling included

E.3. Transportation Phase

Table E.3.: Inventory data of step 2 of transportation phase, for transportation of $1 m^2$ of panel

Route Nr	Route	Transportation Mode	Transported Weight [kg]	Distance [km]	Part
CONVENTIONAL COMPOSITE PANEL					
1	**Michigan (start)** - Halifax	Truck	0,41	2414	Core
	Halifax - Belfast	Ship		4882	
	Belfast - **Kilkeel (finish)**	Truck		80	
2	**Boston (start)** - Belfast	Ship	1,59	5673	Skins
	Belfast - **Kilkeel (finish)**	Truck		80	
BIO COMPOSITE PANEL					
1	Michigan - Halifax	Truck	0,09	2414	Core
	Halifax - Belfast	Ship		4882	
	Belfast - Kilkeel	Truck		80	
2	Hamburg - Belfast	Ship	1,29	2130	Skins
	Belfast - Kilkeel	Truck		80	

Table E.4.: Inventory data of step 3 of transportation phase, for transportation of $1 m^2$ of panel

Route	Distance [km]	Transportation Mode	Conventional Panel - Transported Weight [kg]	Bio composite Panel - Transported Weight [kg]
Kilkeel (start) - Belfast	80	Truck	2	1,38
Belfast - Halifax	4800	Ship	2	1,38
Halifax - Vancouver	6000	Truck	2	1,38
Vancouver - **Everett (finish)**	230	Truck	2	1,38
Correction when aircraft is used (10% of cases)	11110	Aircraft	2	1,38

Table E.5.: Environmental impacts of transporting 1 tonne per 1 km with different transportation modes

Transportation Mode	Carbon Footprint [kgCO2eq/tkm]	Energy [MJ/tkm]
Truck	0,078	1,22
Ship	0,005	0,005
Aircraft	0,58	8,65

E.4. Maintenance Phase

Table E.6.: Environmental impacts for PVC manufacturing, per 1 kg of material

PVC Manufacturing	Carbon Footprint [kgCO2eq]/1kg of material	Energy [MJ]/1kg of material
Polymer extrucion	0,446	5,94
Coarse machining	0,0595	0,794

E.5. DISPOSAL PHASE

Table E.7.: Inventory data for disposal phase, per 1kg of incinerated material

Material	Carbon Footprint emitted [kgCO2eq], per 1kg (from burning)	Energy [MJ], per 1kg (recovered)	Carbon Footprint saved [kgCO2eq], per 1kg[1]	Data source of emitted carbon footprint and energy recovered
CONVENTIONAL COMPOSITE PANEL				
Aramid Fiber Paper	2,65[2]	27,4[2]	12,03	Granta EduPack, Aramid fiber (Kevlar 149)
Phenolic Resin	3,01[2]	31,5[2]	13,83	Granta EduPack, PF (casting resin)
Glass Fiber	-	-1,45	-0,64	-
DecaBDE	-	12,9	5,66	-
PVC film	1,44[2]	17,5[2]	7,68	Granta EduPack, tp-PVC
BIO COMPOSITE PANEL				
PEI	2,89	28,1	12,33	Granta EduPack, Polyetherimide foam
Geopolymer Resin	-	-	-	-
Flax Fiber Yarn	1,46[2]	17[2]	7,46	Granta EduPack, Flax fiber
Non halogenated	-	-	-	-
PVC film	1,44[2]	17,5[2]	7,68	Granta EduPack, tp-PVC

[1] Calculated based on recovered energy and Global electricity mix (Appendix F)
[2] Data noted in Granta EduPack as estimated

E

F

ELECTRICITY MIXES

Table F.1.: Electricity mixes used in the research

	US Electricity Mix	EU Electricity Mix	Global Electricity Mix
kgCO2eq/1kWh	0,3878	0,2750	1,5800
kgCO2eq/1MJ	0,1077	0,0764	0,4389
Mix	(1) 61% combustible fuels (coal, natural gas, petroleum), (2) 21.5% renewable energy source (eia.gov)	(1) 41.9% combustible fuels, (2) 25% nuclear energy, (3) 13.7% wind energy, (4) 13.3% hydro energy, (5) 5.8% solar energy, (6) 0.2% geothermal energy	(1) 48.5% oil, (2) 14.1% natural gas, (3) 13.6% coal, (4) 12.6% biofuels and waste, (5) 9.5% electricity, (6) 1.7% other
Year	2021	2021	2019
Source	Administration, 2022	Agency, 2021; eurostat, 2023	IEA, 2021a, 2021b, 2022

G

Impact Assessment Data

G.1. Raw Material Extraction

Table G.1.: Detailed impact assessment of raw material extraction phase

		Carbon Footprint [kcCO2eq]		Energy [MJ]		Water Usage [l]	
Material	**Weight in 1m2 [kg]**	**per 1m2**	**per seat, 4,522 m2**	**per 1m2**	**per seat, 4,522 m2**	**per 1m2**	**per seat, 4,522 m2**
			CONVENTIONAL COMPOSITE				
Aramid Fiber Paper	0,41	5,62	25,40	404,67	1830,01	404,67	1830,01
Phenolic Resin	0,42	0,82	3,72	22,85	103,32	22,85	103,32
Glass Fiber	0,73	2,29	10,37	72,42	327,48	72,42	327,48
DecaBDE	0,07	0,20	0,91	0,00	0,00	0,00	0,00
PVC film	0,37	1,07	4,85	74,00	334,64	74,00	334,64
TOTAL	*2,00*	*10,01*	*45,25*	*573,93*	*2595,46*	*573,93*	*2595,46*
			BIO COMPOSITE				
Polyetherimide	0,09	1,79	8,10	22,05	99,72	48,69	220,19
Geopolymer Resin	0,6	0,02	0,09	0,30	1,38	8,64	39,07
Flax Fiber Yarn	0,22	0,10	0,46	2,55	11,54	726,00	3283,13
Non halogenated	0,08	0,02	0,09	0,26	1,15	0,00	0,00
PVC film	0,39	1,13	5,11	26,21	118,52	78,00	352,73
TOTAL	*1,38*	*3,06*	*13,85*	*51,37*	*232,31*	*861,33*	*3895,13*

G.2. Manufacturing Phase

Table G.2.: Detailed impact assessment of manufacturing phase

		Carbon Footprint [kgCO2eq]		Electricity [MJ]		Water Usage [l]	
Energy/Waste	**Value for 1m2**	**per 1m2**	**per seat, 4,522 m2**	**per 1m2**	**per seat, 4,522 m2**	**per 1m2**	**per seat, 4,522 m2**
			CONVENTIONAL COMPOSITE				
Energy Requirement [MJ]	57,60	4,40	19,90	57,60	260,48	-	-
Phenolic Resin [kg]	0,24	0,47	2,13	19,32	87,37	13,06	59,04
Hydraulic oil [kg]	0,00392	-	-	-	-	-	-
Wastewater [m3]	0,00000464	-	-	-	-	0,00	0,00
TOTAL		*4,87*	*22,03*	*76,92*	*347,85*	*13,06*	*59,04*
			BIO COMPOSITE				
Energy Requirement [MJ]	82,40	6,29	28,46	82,40	372,63	-	-
Geopolymer Resin [kg]	0,08	0,00	0,01	0,04	0,18	1,15	5,21
Wood and cardboard [kg]	0,00367	0,01	0,04	0,20	0,89	6,57	29,71
Garbage [kg]	0,00319	-	-	-	-	-	-
Flax fabric [kg]	0,00307	0,00	0,01	0,04	0,16	10,13	45,81
TOTAL		*6,31*	*28,52*	*82,67*	*373,87*	*17,85*	*80,73*

G.3. TRANSPORTATION PHASE

Table G.3.: Details of impact assessment of step 2 of transportation phase

		Carbon Footprint [kgCO2eq]		Energy [MJ]	
Route Nr and Description	Route	**per 1m2**	**per seat, 4,522 m2**	**per 1m2**	**per seat, 4,522 m2**
CONVENTIONAL COMPOSITE					
Nr 1 - Core (0,41kg)	Michigan - Halifax	0,00768	0,03473	0,12075	0,54605
	Halifax - Belfast	0,00096	0,00434	0,00100	0,00453
	Belfast - Kilkeel	0,00025	0,00115	0,00400	0,01810
Nr 2 - Skins (1,59kg)	Boston - Belfast	0,00433	0,01958	0,00451	0,02040
	Belfast - Kilkeel	0,00099	0,00446	0,01552	0,07018
TOTAL		*0,01421*	*0,06427*	*0,14578*	*0,65925*
BIO COMPOSITE					
Nr 1 - Core (0,09kg)	Michigan - Halifax	0,00169	0,00762	0,02651	0,11986
	Halifax - Belfast	0,00021	0,00095	0,00022	0,00099
	Belfast - Kilkeel	0,00006	0,00025	0,00088	0,00397
Nr 2 - Skins (1,29kg)	Hamburg - Belfast	0,00137	0,00621	0,00137	0,00621
	Belfast - Kilkeel	0,00080	0,00364	0,01259	0,05694
TOTAL		*0,00413*	*0,01868*	*0,04157*	*0,18798*

Table G.4.: Details of impact assessment of step 3 of transportation phase

	Carbon Footprint [kgCO2eq]		Energy [MJ]	
Route	**per 1m2**	**per seat, 4,522 m2**	**per 1m2**	**per seat, 4,522 m2**
CONVENTIONAL COMPOSITE				
Kilkeel - Belfast	0,01	0,06	1,22	5,52
Belfast - Halifax	0,05	0,22	0,01	0,02
Halifax - Vancouver	0,94	4,23	1,22	5,52
Vancouver - Everett	0,04	0,16	1,22	5,52
Correction when aircraft is used (10% of cases)	1,29	5,83	192,20	869,18
TOTAL	*2,32*	*10,50*	*3,67*	*885,76*
BIO COMPOSITE				
Kilkeel - Belfast	0,01	0,04	0,20	0,88
Belfast - Halifax	0,03	0,15	0,05	0,22
Halifax - Vancouver	0,65	2,92	14,64	66,21
Vancouver - Everett	0,02	0,11	0,56	2,54
Correction when aircraft is used (10% of cases)	0,89	4,02	132,62	599,74
TOTAL	*1,60*	*7,24*	*15,44*	*669,58*

Table G.5.: Summary of considered stages of transportation phase

	Carbon Footprint [kgCO2eq]		Energy [MJ]	
Step Nr	**per 1m2**	**per seat, 4,522 m2**	**per 1m2**	**per seat, 4,522 m2**
2	0,01	0,06	0,15	0,66
3	2,32	10,50	207,65	939,03
TOTAL	*2,34*	*10,56*	*207,79*	*939,69*

G.4. MAINTENANCE PHASE

Table G.6.: Details of impact assessment of maintenance phase

	Carbon Footprint [kgCO2eq]	**Energy [MJ]**	**Water Usage [l]**
	CONVENTIONAL COMPOSITE		
Raw Material Extraction [1]	48,29	1118,88	3330
Manufacturing [2]	8,42	112,12	-
Transportation [3]	19,44	1729,88	-
End-of-life [4]	-103,91	-291,38	-
TOTAL, per 45 panels, per 5 years	*-27,76*	*2669,50*	*3330*
TOTAL impact per seat, per 5 years	*-1,54*	*148,31*	*185,00*
	BIO COMPOSITE		
Raw Material Extraction [1]	50,90	1179,36	3510,00
Manufacturing [2]	8,87	118,18	-
Transportation [3]	20,42	1883,52	0,00
End-of-life [4]	-109,52	-307,13	-
TOTAL, per 45 panels, per 5 years	*-29,34*	*2873,94*	*3510,00*
TOTAL impact per seat, per 5 years	*-1,63*	*159,66*	*195,00*

[1] Own calculation: *(45panels)*(carbon footprint of PVC extraction for 1m2 panel (Table G.1))*. Example for the conventional panel: $45*1,07 = 48,29$. The same logic for energy and water calculations.
[2] Own calculation: *(45panels)*(weight of PVC in 1m2 panel (Table G.1))*(carbon footprint of PVC manufacturing (polymer extrusion + coarse machining, Table G.6))*. Example for the conventional panel: $45*0,37*(0,446+0,0595) = 8,42$. The same logic for energy and water calculations.
[3] Own calculation: *(45panels)*(carbon footprint of all transportation steps for 1m2 panel (Table G.5))*(weight of PVC in 1m2 panel (Table G.1))/(total weight of 1m2 panel)*. Example for the conventional panel: $45*2,34*0,37/2 = 19,44$ The same logic for energy and water calculations.
[4] Own calculation: *(45panels)*(total carbon footprint of PVC end-of-life for 1m2 panel (Table G.7))*. Example for the conventional panel: $45*(-2,43) = -103,91$. The same logic for energy and water calculations.

G.5. DISPOSAL PHASE

Table G.7.: Details of impact assessment of disposal phase

		Carbon Footprint emitted [kgCO2eq] (from burining)		**Energy [MJ] (recovered)**		**Carbon Footprint saved [kgCO2eq]**		**Carbon Footprint total [kgCO2eq]**	
Material	**Weight in 1m2 [kg]**	**per 1m2**	**per seat, 4,522 m2**	**per 1m2**	**per seat, 4,522 m2**	**per 1m2**	**per seat, 4,522 m2**	**per 1m2**	**per seat, 4,522 m2**
				CONVENTIONAL COMPOSITE					
Aramid Fiber Paper	0,41	1,09	4,91	11,23	50,80	4,93	22,30	-3,84	-17,38
Phenolic Resin	0,42	1,26	5,72	13,23	59,83	5,81	26,26	-4,54	-20,54
Glass Fiber	0,73	0	0	-1,06	-4,79	-0,46	-2,10	0,46	2,10
DecaBDE	0,07	0	0	0,90	4,08	0,40	1,79	-0,40	-1,79
PVC film	0,37	0,53	2,41	6,48	29,28	2,84	12,85	-2,31	-10,44
TOTAL	*2,00*	*2,88*	*13,04*	*30,78*	*139,21*	*13,51*	*61,10*	*-10,63*	*-48,06*
				BIO COMPOSITE					
Polyetherimide	0,09	0,26	1,18	2,53	11,44	1,11	5,02	-0,85	-3,84
Geopolymer Resin	0,60	0	0	0	0	0	0	0	0
Flax Fiber Yarn	0,22	0,32	1,45	3,74	16,91	1,64	7,42	-1,32	-5,97
Non halogenated	0,08	0,00	0,00	0,55	2,50	0,24	1,10	-0,24	-1,10
PVC film	0,39	0,56	2,54	6,83	30,86	3,00	13,55	-2,43	-11,01
TOTAL	*1,38*	*1,14*	*5,17*	*13,65*	*61,71*	*5,99*	*27,08*	*-4,85*	*-21,92*

H

CBA DATA

H.1. Fuel Price Data

Table H.1.: Fuel prices in years 2018-2023. Based on "Jet Fuel - Daily Price - Commodity Prices - Price Charts, Data, and News - IndexMundi", n.d.

Month	Month Nr	Price (cents/gallon)	Month	Month Nr	Price (cents/gallon)
Apr-18	1	202	Oct-20	31	105
May-18	2	216	Nov-20	32	113
Jun-18	3	209	Dec-20	33	132
Jul-18	4	210	Jan-21	34	142
Aug-18	5	212	Feb-21	35	160
Sep-18	6	219	Mar-21	36	166
Oct-18	7	225	Apr-21	37	167
Nov-18	8	195	May-21	38	175
Dec-18	9	170	Jun-21	39	186
Jan-19	10	178	Jul-21	40	189
Feb-19	11	191	Aug-21	41	182
Mar-19	12	190	Sep-21	42	200
Apr-19	13	198	Oct-21	43	230
May-19	14	197	Nov-21	44	219
Jun-19	15	182	Dec-21	45	210
Jul-19	16	191	Jan-22	46	245
Aug-19	17	180	Feb-22	47	268
Sep-19	18	188	Mar-22	48	350
Oct-19	19	186	Apr-22	49	391
Nov-19	20	182	May-22	50	390
Dec-19	21	189	Jun-22	51	412
Jan-20	22	178	Jul-22	52	348
Feb-20	23	151	Aug-22	53	334
Mar-20	24	95	Sep-22	54	326
Apr-20	25	61	Oct-22	55	372
May-20	26	69	Nov-22	56	316
Jun-20	27	98	Dec-22	57	290
Jul-20	28	108	Jan-23	58	354
Aug-20	29	111	Feb-23	59	279
Sep-20	30	101	Mar-23	60	268

H.2. DETAILED CBAS

Table H.2.: Detailed fCBA for flights under EU ETS trading scheme

		2025 Year 0	2026 Year 1	2027 Year 3	2028 Year 3	2029 Year 4	2030 Year 5	TOTAL from 2025-2030	Value of x_1
Costs									
More expensive bio business class seat * 18 seats		-18x_1							
Benefits									
Saved Fuel Cost €$_{2023}$	Low		7408	8020	8631	9243	9855		
	Baseline		8231	8911	9590	10270	10950		
	High		9054	9802	10549	11297	12045		
Saved Carbon Fees €$_{2023}$	Low		2325	2325	2325	2325	2325		
	Baseline		2583	2583	2583	2583	2583		
	High		2842	2842	2842	2842	2842		
Cumulative Costs		-18x_1						-18x_1	
Cumulative Benefits	Low		9733	10345	10956	11568	12180	54781	3043,41
	Baseline		10814	11494	12174	12854	13533	60868	3381,57
	High		11896	12643	13391	14139	14886	66955	3719,73

Table H.3.: Detailed sCBA for flights under EU ETS trading scheme

		2025 Year 0	2026 Year 1	2027 Year 3	2028 Year 3	2029 Year 4	2030 Year 5	TOTAL from 2025-2030	Value of x_2
Costs									
More expensive bio business class seat * 18 seats		-18x_2							
Benefits									
Saved Fuel Costs €$_{2023}$	Low		7408	8020	8631	9243	9855		
	Baseline		8231	8911	9590	10270	10950		
	High		9054	9802	10549	11297	12045		
Saved Carbon Fees €$_{2023}$	Low		2325	2325	2325	2325	2325		
	Baseline		2583	2583	2583	2583	2583		
	High		2842	2842	2842	2842	2842		
Saved Environmental Costs €$_{2023}$	Low		0,235	0,243	0,251	0,260	0,269		
	Baseline		0,608	0,629	0,651	0,674	0,698		
	High		1,003	1,038	1,074	1,112	2,151		
Cumulative Costs		-18x_2						-18x_2	
Cumulative Benefits	Low		9733	10345	10957	11568	12180	54783	3043,48
	Baseline		10815	11495	12174	12854	13534	60872	3381,75
	High		11897	12644	13392	14140	14888	66960	3720,03

Table H.4.: Test case of fCBA, when carbon fees are set to 0

		2025 Year 0	2026 Year 1	2027 Year 3	2028 Year 3	2029 Year 4	2030 Year 5	TOTAL from 2025-2030	Value of x'_1
Costs									
More expensive bio business class seat * 18 seats		-18x'_1							
Benefits									
Saved Fuel Costs €$_{2023}$	Low		7408	8020	8631	9243	9855		
	Baseline		8231	8911	9590	10270	10950		
	High		9054	9802	10549	11297	12045		
Saved Carbon Fees €$_{2023}$	Low		0	0	0	0	0		
	Baseline		0	0	0	0	0		
	High		0	0	0	0	0		
Cumulative Costs		-18x'_1						-18x'_1	
Cumulative Benefits	Low		7408	8020	8631	9243	9855	43156	2398
	Baseline		8231	8911	9590	10270	10950	47951	2664
	High		9054	9802	10549	11297	12045	52747	2930

Table H.5.: Test case of sCBA, carbon fees set to 0 and use phase included

		2025 Year 0	2026 Year 1	2027 Year 3	2028 Year 3	2029 Year 4	2030 Year 5	TOTAL from 2025-2030	Value of x'_2
Costs									
More expensive bio business class seat * 18 seats		-18x'_2							
Benefits									
Saved Fuel Costs €$_{2023}$	Low		7408	8020	8631	9243	9855		
	Baseline		8231	8911	9590	10270	10950		
	High		9054	9802	10549	11297	12045		
Saved Carbon Fees €$_{2023}$	Low		0	0	0	0	0		
	Baseline		0	0	0	0	0		
	High		0	0	0	0	0		
Saved Environmental Costs €$_{2023}$	Low		759	786	813	842	871		
	Baseline		1967	2036	2107	2180	2257		
	High		3243	3357	3474	3596	3722		
Cumulative Costs		-18x'_2						-18x'_2	
Cumulative Benefits	Low		8167	8805	9444	10085	10726	47227	2624
	Baseline		10198	10946	11697	12450	13207	58498	3250
	High		12297	13158	14024	14893	15766	70139	3897

H.3. SENSITIVITY ANALYSIS DATA

Table H.6.: Case 1 of sensitivity analysis - fCBA for flights under CORSIA offsetting program

		2025 Year 0	2026 Year 1	2027 Year 3	2028 Year 3	2029 Year 4	2030 Year 5	TOTAL from 2025-2030	Value of y_1
Costs									
More expensive bio business class seat * 18 seats		$-18y_1$							
Benefits									
Saved Fuel Costs €$_{2023}$	Low		7408	8020	8631	9243	9855		
	Baseline		8231	8911	9590	10270	10950		
	High		9054	9802	10549	11297	12045		
Saved Carbon Fees, CORSIA €$_{2023}$	Low		41	45	49	54	59		
	Baseline		106	116	127	139	153		
	High		712	780	854	935	1024		
Cumulative Costs		$-18y_1$						$18y_1$	
Cumulative Benefits	Low		7449	8064	8680	9297	9914	43404	2411
	Baseline		8337	9027	9718	10409	11102	48593	2700
	High		9766	10582	11404	12232	13069	57053	3170

Table H.7.: Case 2 of sensitivity analysis - fCBA for flights under Whitehouse Bill's carbon fees

		2025 Year 0	2026 Year 1	2027 Year 3	2028 Year 3	2029 Year 4	2030 Year 5	TOTAL from 2025-2030	Value of y_2
Costs									
More expensive bio business class seat * 18 seats		$-18y_2$							
Benefits									
Saved Fuel Costs €$_{2023}$	Low		7408	8020	8631	9243	9855		
	Baseline		8231	8911	9590	10270	10950		
	High		9054	9802	10549	11297	12045		
Saved Carbon Fees, Whitehouse Bill €$_{2023}$	Low		1727	1796	1868	1942	2020		
	Baseline		2057	2160	2268	2381	2500		
	High		1828	1938	2054	2178	2308		
Cumulative Costs		$-18y_2$						$-18y_2$	
Cumulative Benefits	Low		9135	9815	10499	11185	11875	52509	2917
	Baseline		10288	11071	11858	12651	13450	59319	3295
	High		10882	11740	12604	13475	14353	63053	3503

Table H.8.: Case 3 of sensitivity analysis - fCBA for flights when no carbon fees are applies

		2025 Year 0	2026 Year 1	2027 Year 3	2028 Year 3	2029 Year 4	2030 Year 5	TOTAL from 2025-2030	Value of y_3
Costs									
More expensive bio business class seat * 18 seats		$-18y_3$							
Benefits									
Saved Fuel Burn Costs €$_{2023}$	Low		7408	8020	8631	9243	9855		
	Baseline		8231	8911	9590	10270	10950		
	High		9054	9802	10549	11297	12045		
Saved Carbon Fees, no tax €$_{2023}$	Low		0	0	0	0	0		
	Baseline		0	0	0	0	0		
	High		0	0	0	0	0		
Cumulative Costs		$-18y_3$						$-18y_3$	
Cumulative Benefits	Low		7408	8020	8631	9243	9855	43156	2398
	Baseline		8231	8911	9590	10270	10950	47951	2664
	High		9054	9802	10549	11297	12045	52747	2930