Sustainability Integration in Engineering Practice

A comparative life cycle assessment with the case study of a wing rib

Jaskrit Singh Bakshi

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by

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Abstract

Having seen exponential growth in demand for air travel, the aviation industry has found itself trying to find a balance between economic growth, technological development, and environmental sustainability. This saw a shift in attention towards materials such as fiber reinforced composites, predominantly thermoset in the past with higher strength-to-weight fractions. Relatively recent was the introduction of high-performance fiber reinforced aryletherketone thermoplastic polymer composite materials possessing more promising prospects of circularity in addition to the lightweighting capabilities. But as is, these only form for qualitative claims with no indication on how the ecological effects would pan out over the life cycle phases objectively, as well as on a relative scale. Extending beyond the orthodox considerations and measures of aircraft performance, life cycle assessment studies encompass a comprehensive analysis of the environmental impact associated with aerospace products through the various phases of their life cycle including material extraction/production, manufacturing, operation, and the respective end-of-life treatment. The primary objective is to quantify the environmental impact of the system, offering a holistic view of the emissions, energy demand, and resource consumption. To this end, this study constructed a comparative environmental profile, modelling for five material/manufacturing systems, namely numerically machined aluminium alloy, autoclave cured and resin transfer molded carbon fiber reinforced epoxy, autoclave consolidated, and press consolidated carbon fiber reinforced polyetherketoneketone over the cradle-to-gate and the cradle-to-end of service phases in an attempt to find the best variant from an environmental perspective, while adding a novel, semi-quantitative, robust framework of data quality assessment to the state-of-the-art. Notably, primary data was used to model for all foreground processes while high time and resource investments yielded high quality datasets for background processes.

Preface

Standing at the threshold of concluding this project fills me with a sense of great accomplishment and gratitude. This journey has been both challenging and rewarding, pushing the boundaries of my intellectual curiosity and testing the limits of my perseverance. This work is the outcome of months of research, analysis, and introspection. It would not have been possible without the support and guidance of numerous individuals whom I would like to acknowledge with deep appreciation. First and foremost, I express my sincere gratitude to my supervisors, Dr.ir. Thomas de Bruijn, for his continued trust, invaluable guidance, unwavering support, and insightful feedback throughout the entire process allowing me to function under the perfect balance between freedom of thought and mentoring where needed, and to Dr.ir. Irene F. Villegas for her valuable insight and patience. More than worthy of a mention are the members from academia and industry alike whose work laid the foundation for this project to build upon. Additionally, I would like to acknowledge the colleagues at the Global Technology Centre, HGV whose contributions have played a crucial role in the realization of this project. To my friends (TSAET), nothing but love for being my source of comfort and content through and through. But most importantly, my deepest appreciation goes out to Mmaa, Papa and Didi for being the pillars keeping all of this up, and Nanu, one of the bigger reasons for me to have gotten where I have. This accomplishment is as much theirs, as it is mine.

Jaskrit Singh Bakshi
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1 Introduction

The aviation industry, especially the commercial sector, has seen magnificent growth in demand/service in the last decades, the number of passengers using the facilities going from about 100 million in 1960 to 4.6 billion in 2019 [1]. The steep rise has been fruitful in matters concerning revenue models and technological growth within the sector as well as upstream but has carried severe ecological consequences. Based on the estimates from the International Council on Clean Transportation, global carbon dioxide emissions from commercial aviation alone have gone from 707 gigatons in 2013 to 920 gigatons in 2019, increasing by close to 30% [2]. For the year 2018, aviation contributed about 2.4% of the global carbon dioxide emissions. When looking at a more comprehensive impact concerning the global warming effects, the report in the journal of Atmospheric Environment from January 2021 estimated aviation to have accounted for 3.5% of the total anthropogenic warming in 2018 [3]. To place this in an objective scope, the goal set as part of the Paris Agreement, 2015 was to restrict the net rise in global temperatures to under 1.5 degrees celsius, implying a carbon budget of 200 to 350 gigatons between the years 2016 and 2100. If the aviation industry were to continue on growth trends observed in the pre-Covid-19 era, it is expected to deplete a quarter of this quota by the year 2050, emitting about 56 gigatons between 2016 and 2050 [4]. There is hence a sense of urgency in treating matters regarding sustainability, especially those tied to environmental consequences, from stakeholders representing academia as well as the industry. The report scrutinizing the contribution of the global aviation sector to global warming effects [4] also described what they termed as “A Roadmap for Decarbonization”. In the short term, they recommended deployment of cleaner aviation technology and lower-carbon fuels to improve operational efficiency. This could be achieved by decommissioning older, less efficient aircraft from commercial airline fleets, and retrofitting existing ones with wingtips, electrical taxiing systems, etc. to facilitate improved environmental performance. In addition, government bodies could get involved, setting policies with the goal of improving transparency in the matters of environmental performance.

This has seen extensive attention being directed towards the development of the tool that is life cycle assessment (LCA). Extending beyond the orthodox considerations and measures of aircraft performance, LCA studies encompass a comprehensive analysis of the environmental impact associated with aerospace products through the various phases of their life cycle including material extraction/production, manufacturing, operation, and the respective end-of-life treatment. The primary objective is to quantify the environmental impact of the system, offering a holistic view of the emissions, energy demand, and resource consumption. The results are known to catalyze innovation, stimulating the development of “greener” technologies including alternate material systems, propulsion technologies, and energy sources. As for the technological developments, two avenues are being invested in to minimize, and eventually neutralize the environmental footprint of aviation. One is the deployment of alternate, carbon-free fuel systems, while the other is lightweighting techniques to reduce fuel consumption in-flight. On the front of propulsion systems, sustainable aviation fuels (SAFs), electrical propulsion and hydrogen-powered flight are some of the viable options being explored but are still at nascent stages in terms of development. As for materials, composites, both thermoset and thermoplastic, have invited remarkable interest as successors to conventional aluminum alloys owed to superior specific properties and resistance to corrosion and fatigue, but still lag on subjects of damage prediction and non-recurring costs with regards to fabrication [5].

This discourse shall attempt to apply the framework of LCA on a structural component, constructing a comparative assessment for the viability of a given scenario from the perspective of environmental sustainability that can be fed into the respective decision-making process when allocating resources for product development. The investigation was conducted in collaboration with GKN Aerospace©, contributing to their involvement as the lead to Work Package 4.5 of the Mobility Fund entitled “Thermoplastic Material for Sustainable Aviation”, focused on analyzing the influence of thermoplastic composite technology on sustainability, Collins Aerospace©and Toray Advanced Composites©being involved as partner organisations in the larger deliverable of the work package. This begins with Part I summarizing the state-of-the-art on the conventional as well as novel material and manufacturing systems within aerospace, that for the maturity of LCA as a tool, followed by the identification of knowledge gaps, informing the research questions quoted thereafter. This is succeeded by the specifics of the methodology taken up through the phase of conduction of the analysis being detailed, drawing this part to a close. Part II opens with justification of the selection of the case study and insight into the systems modelled per scenario before delving into each of the phases of the life cycle analysis. Part III circles back to the research questions, the results being analyzed and placed in perspective of the current knowledge base before addressing some limitations of the conducted study and aspects worth exploring for future research. This entire discussion is then tied together formulating a conclusion.

Part I

Scientific Background and Research Framework

2

State-of-the-Art

A detailed literature survey was conducted and documented as a precursor to this project. This section summarizes some of the more important findings in the existing knowledge frame of relevant material and processing systems, those for life cycle assessment, followed by the definition of identified gaps in research to be addressed in the scope of this project.

2.1. Material and Manufacturing Technologies

The product trinity said to be formed by the choice of design, material system, and manufacturing technique, as in Figure 2.1, is an illustration of the inherent interdependence between these phases, each impacting the next as well as the former. There has been continuous interest in lightweighting to improve operational efficiency, from perspectives of cost as well as environmental sustainability. Materials, and hence manufacturing techniques, have hence evolved significantly over the years, from the first flying aircraft, courtesy of the Wright Brothers, being a wood and covering fabric construction to modern day metal alloy and fiber reinforced composite structures [6].

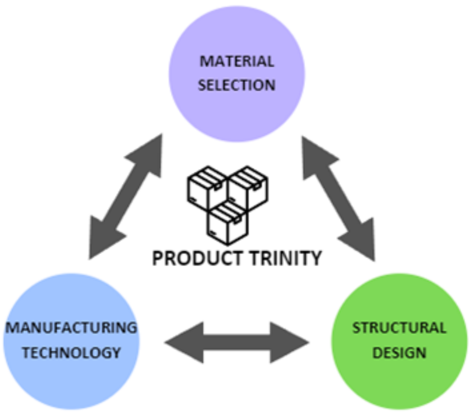

Figure 2.1: Product trinity - Structural design, material selection, and manufacturing technique

Aluminum alloys, especially the 7xxx series, have found their space in load-bearing structures across aircraft classes owed to high strength-to-weight ratios and relatively low cost. The major drawback with metal alloys was identified to be their susceptibility to corrosion and fatigue damage necessitating continuous maintenance activities [7]. Sustained search for creative solutions of fabricating aluminum structures has had two primary objectives, *improved structural integrity* and *reduced energy demand*, and hence reduced cost [5]. This has seen the trends move towards the ability to build larger structures with fewer parts or joining techniques enabling expedited operations. Machining focused on efficient processing of thicker plates has been the choice for simpler geometries, while forming techniques have attracted attention for the processing of more complex topologies [8]. High-speed machining has evolved to be cost-effective production of integral sections using thick aluminum ingots as the feed, offering benefits such as shorter machining times, the capability to process thin-walled components, and a consistent, high-quality surface finish [9]. Based on the blank temperature at the time of processing, forming techniques have been classified into hot and cold forming. Cold forming was stated to be appropriate for lower strength aluminium grades in a high-volume environment attributed to low processing times and associated cost. Hot forming pertains to the blank being heated to temperatures close to those for heat treatment, known to improve formability, and even ductility for certain grades [5].

Composite materials, commonly defined as structural materials with distinct properties resulting from the combination of two or more components that don't naturally mix, have been the most attractive of the explored alternatives. They typically consist of a reinforcing phase, responsible for imparting the load-bearing properties, and a matrix phase that facilitates load transfer acting as a binding phase, illustrating superior specific properties that can even be tailored to suit a specific application, while being resistant to fatigue and corrosion damage [10]. The drawbacks here were stated to be high costs of production and complexity in prediction of damage parameters in-service. Continuous efforts are being invested to address these concerns, innovating on the fronts of reducing manufacturing times and associated cost, while also developing models for damage tolerant designs [11]. Braga et al [12] performed a review on the various design philosophies and their influence on the advancements in matters of safety and prolonged service life of aircraft, highlighting the importance of damage tolerant designs not just for the scope of future designs, but also for airworthiness assessment of the existing fleet. They identified the biggest knowledge gap to be associated with material behavior and failure modes. The reinforcement phase, observed to constitute 60 to 70% of the product volume for high-performance applications, generally consists of continuous, slender fibers made out of either glass, aramid or carbon precursors, the choice depending upon the requirements posed by the function to be performed by the product. On the other hand, the matrix phase was commonly observed to be comprised of polymer compounds that may be thermosetting or thermoplastic by nature. Thermosetting polymers undergo an irreversible curing process under designed processing conditions, the molecular chains chemically cross-linking while transitioning from a liquid or soft solid state to a solid state [10]. Conventional aerospace-grade epoxies tend to require elevated temperatures and pressure environments for their cure. The baseline for facilitating the same has been autoclave processing, known to produce high-quality products but high cycle times and associated costs have been a limiting factor [13]. Originally developed to keep up with high-volume production in automobile applications, resin transfer moulding is an out-of-autoclave manufacturing technique that optimizes the cycle times [14]. The limiting factor with this process, one of the major reasons for the struggle with its uptake by the aerospace industry, is limitation on the viscosity of the epoxy for reasonable injection pressures, observed to affect mechanical properties of the end-product. The change of state, from a liquid or glassy state to a solid, for thermoplastic polymers is a reversible, physical change. This has been stated to impart them with an intrinsic toughness, attributable to their non-cross-linked nature, rendering them particularly suitable for applications where damage tolerance is a paramount consideration [15]. The overall manufacturing process for thermoplastic composites has hence been divided into three phases, a reductive scenario to aid understanding, the first being heating to melt the polymer phase, followed by pressurization to compact and consolidate the product, and ultimately cooling at a suitable rate to avoid internal stresses. For thermoplastics as well, the autoclave has been the baseline attributed to the high quality of products while ensuring repeatability and consistency. Fernandez et al [16] described the production of autoclave consolidated demonstrator components employing polyphenylene sulphide (PPS) matrix-based thermoplastic composites, drawing attention to the significantly shorter cycle times compared to thermoset counterparts. To exploit the properties to further reduce the cycle times and corresponding costs, out-of-autoclave processing is also being explored for thermoplastic variants. Press forming is one such practice wherein, the blank is heated to melt/processable viscosity in an infrared oven, compacted under high pressures, and then cooled at a suitable rate. Alternatively, a press consolidation cycle, stated to be similar to a resin transfer moulding process, could be used. Being developed at GKN Aerospace©, the process entails placing an unconsolidated blank in a press that is heated using an integrated system, compacted by applying pressure using a bladder system before cooling to room temperature [17].

2.2. Life Cycle Assessment

2.2.1. Product Life Cycle Assessment and Waste Stream Processing

Life cycle assessment, as a tool for quantification of environmental impact, has seen widespread application in academic and industrial frameworks. Several studies have been published modelling various life cycle phases in objective as well as comparative scopes, the results being used to steer product development, and marketing strategies. The work of Stefanidi [18] provided a foundation for this work, developing a preliminary tool for comparing the environmental sustainability of aerostructures produced via various material-manufacturing routes, including metals and composites, finally applying it for the case study of Rib 14 of Airbus' Wing of Tomorrow© program. As for results, they concluded that manufacturing with aluminium, especially using machining as the primary technology, to be ecologically costly due to a poor buy-to-fly ratio. Despite a good infrastructure surrounding it, the process of recycling was expected to consume a considerable amount of energy, resulting in a high global warming potential (GWP) measured in carbon dioxide-equivalent emissions. Composite manufacturing technologies were found to have significantly lower environmental impacts during the production phase compared to machining aluminium, the benefits further substantiated by lightweighting opportunities. This study was built upon by Arblaster [19], the most crucial study in the state-of-the-art for the scope of this research. They also performed a sustainability analysis for the case of a wing rib including four material/manufacturing scenarios over its entire life cycle but shifting focus to the development of a more comprehensive understanding of the interdependence of material choices, manufacturing routes and the propulsion system transition scenarios within aviation. Their primary focus was the relevance of the concept of lightweighting and the downstream impact of the same on the footprint of the operational phase. They concluded, as a result of a novel break-even analysis framework, a weight difference of 3% to be enough for a product to be preferred over counterparts across environmental impact categories. Howe et al [20] conducted an analysis for the case study of a commercial airliner, finding the impact contributed by the operation to be as high as about 99%. Another interesting statistic put forth was the impact of the manufacturing phase being comparable to only 6.5 days of operation. A.J. Timmis et al [21] presented a life cycle analysis of a prospective all-composite Boeing 787 Dreamliner©, also spotlighting the reduced impact of carbon fiber reinforced plastics in single score impact, despite the higher environmental impact in the manufacturing phase, due to a reduced weight and hence, decreased fossil fuel use. L. Scelsi et al [22] constructed a comparative analysis between carbon fiber reinforced polymer (CFRP), glass reinforced laminate (GLARE), and Aluminium 2024 by defining the functional unit to a defined panel of undisclosed dimensions. They managed to put a number on the break-even analysis, being 70,000 km and 240,000 km for CFRP and GLARE, respectively, to nullify the impact-intensive material and production phases. Each of these contributions essentially reinforce the idea concerning the relevance of the weight of a flying product as a dominant factor for determining efficiency, not just for operation, but also from an environmental perspective when the service life is modelled into the system.

Even though the relative impact for the cradle-to-gate phases over the cradle-to-grave(or cradle) system is negligible, they can still be attributed to a great degree of objective consequence and must not be overlooked. A trend highlighting the footprint-intensive mass-specific production of raw materials for composite products in comparison of the metal counterparts came under scrutiny, as much as 90% of the total footprint being taken up by carbon fiber prepreg and/or fabric production in some cases [23]. Vita et al [24], in a comparative scenario, weighed up pressure bag molding and autoclave curing as carbon fiber reinforced product manufacturing technologies, interestingly having the manufacturing of the moulds within their system boundaries to understand that influence as well. While their inventory and results are communicated well, being mindful of the fact that energy demand for autoclave curing was modelled based on secondary data with over a decade between the publication dates compared to primary, recent data used to model the pressure bag molding energy demand and might not be the most representative comparison is important. Interesting insight was brought forth by Vassilopoulos [25], focusing on the thermostamping process of carbon fiber reinforced PPS from an environmental perspective, aggregating a high-quality life cycle inventory using a variety of sources including experimentally measured data, literature, and databases in the production of a part of about 250x200x4 mm3. Their results indicated the hotspots to be energy consumption during the heating and stamping process. Another initiative from Ogugua et al [26] compared a thermoset (carbon fiber reinforced epoxy) and thermoplastic composite (carbon fiber reinforced PPS) aircraft panel. The material data was sourced from literature while the autoclave data for curing and the hot press data for consolidation were notably aggregated from measurements, the results indicating an energy demand difference of about 15% in favor of the thermoplastic variant, even though it performed worse in the material phase. Credit to the practitioners on being able to set up an infrastructure to gather primary data for foreground activities, the findings only adding credibility to existing claims within the discipline. Owed to shear lack of representative data in the open source, a vast majority of the studies relied upon other publications or aggregated databases for inventory aggregation. But sources used for data collection and characterization were often not cited with exactitude, compromising the applicability of the results, making the use such computations by other studies highly uncertain along the chain. Transparency and precision concerning matters of system definition and inventory accumulation were often overlooked across articles, also playing in heavily for studies taking up comparative scenario-based analyses, downplaying the importance of similarity of quality of inventories aggregated for the systems to make for more ”like-for-like” comparisons. Moreover, a majority of studies were seen to either produce objective impact results or compare systems with little diversity. This essentially leads to these studies adding to the knowledge base as isolated entities, missing an important aspect that is widespread applicability, lagging on the ability to build representative systems with transparent communication of inventory aggregation, and ignorance with regards to the quality of the datasets, understood to have a high degree of correlation with credibility of the results.

Nascent in its uptake but solving the conspicuous problem of data availability, processing modelling has been taken up for predicting inventory data for prospective life cycle assessment studies, especially for scenario modelling wherein trade-offs are to be made at early, and/or theoretical stages. Ogugua et al [27] proposed two mathematical models to predict the energy consumption during autoclave curing in carbon fiber reinforced polymer manufacturing. These models included an analytical one based on Fourier heat equations, and another based on the MRT Lattice Boltzmann Method (LBM), the results validated with a baseline value based on measured data. The analytical model, although less accurate, was seen to demand a considerably lower computational effort, useful for applications needing first order estimates. Remarkably, computations on dependence of the energy demand on chamber geometry as well as recipe parameters were also performed to add a layer of robustness. Yan He et al [28] proposed a comprehensive model for computing the environmental impact for machining processes, developing and validating a process-scenario oriented database to assist with decision-making. Yet again, these techniques, as valuable as they are objectively, lack the foundation of credible data for model verification and assessment of applicability of these models. As they stand, the training and verification sample sets based on primary data for these models are too small to instil confidence in an independent practitioner.

Per the buy-to-fly ratio of the specific route, the amount of manufacturing waste produced along the life cycle stages varies for a given product system. Rybicka et al [23] illustrated a systematic approach to collect data concerning these waste streams, the novelty lying in its use of existing methods to explore the potential for diversifying material treatment in composite waste management. The case studies revealed three waste outputs related to fibers: dry fibers, cuts from fiber material sheets, and cured/consolidated composite waste. The aggregated data and the management system promote development of strategies concerning not just waste minimization, but also recycling/downcycling of based on waste type. de Bruijn et al [29] studied the recycling of carbon fiber reinforced PPS consolidated laminate by means of shredding, followed by low shear mixing process to retain the fiber length and properties. The composition of the input materials was observed to have negligible influence on the mechanical properties of the product, whether cut semipreg, shredded laminate, or unidirectional pellets were used. The processing phase was stated to be convenient, emphasizing the resilience of the examined low-shear process, applicable to both new and recycled thermoplastic composites, and permits the achievement of desirable structural traits. Bianchi et al [23] furthered these approaches in combination, evaluating the ecological feasibility of recycling activities using scrap from the prepreg cutting stage of part production. Three scenarios for processing were considered for comparison: compression molding production with virgin prepreg, compression molding production with recovered prepreg scraps and autoclave processing with virgin prepreg. Various environmental indicators, including cumulative energy demand, global warming potential, and ReCiPe, were used to assess the environmental impacts of these scenarios, both at midpoint and endpoint levels, the innovative compression molding process utilizing prepregs scraps boasting the most environmentally friendly outcomes across all considered impact categories. Another interesting waste stream is the end-of-life waste recovered off of decommissioned aircraft. As much as 85% (by weight) of an aircraft can be recovered, per the findings documented in Airbus' report [30]. Approaches concerning composites have an inherent uncertainty due to a majority of aircraft with meaningful composite weight fractions are still in service. End-of-life aircrafts were recognized as valuable sources of aluminum and different materials by Sabaghi et al [31] as well. Acknowledging the complex structure of the carcass to be dealt with, they formulated a practical methodology focused on segregation and grouping of alloys into their respective family series before being passed on for further processing. They identified eight disassembling strategies for evaluation on the grounds of environmental sustainability. The recommended framework accounts for a variety of variables, outside of the generic environmental indicators, such as liabilities to entertain, interests of the decision-makers and policymakers in the company, when determining the most appropriate solution per case. The aforementioned efforts are characteristic to the increased interest and relevance of development of methods targeting ”leaner” systems and circularity, promoting value-addition to the large proportions of waste streams otherwise bound to disposal at landfills or incineration for thermal energy recovery. However, no real insight into the prospective methods for allocation of burdens and benefits between the primary and co-products, that would need to be taken up if and when these activities come into play, was provided.

2.2.2. Life Cycle Inventory - Data Quality Assessment

In a report attempting to develop a formalized framework, the Society of Environmental Toxicology and Chemistry defined data quality as as the degree of confidence in the input dataset as a whole, data quality Assessment, hence, being a systematic approach to evaluate the suitability of the data being used to see if it qualifies and fulfils the intended purpose. The purpose of developing a data quality assessment framework was attributed to the amount of diversity in data, and therefore, it is necessary to have a methodical, logical, formalized and repeatable format in place [32]. The level of quality is influenced by the amount of effort allocated to the study, which is further a function of data availability, time constraints, budget and the purpose of the study. Although the relationship between the quality of data and the quality of the results generated is not causal, they can be said to have a strong correlation, i.e., a higher quality input dataset would generate more representative and credible results. The ISO series [33] defines ten key categories, in a broad perspective, to be addressed when evaluating data quality, especially if the study is intended to make comparative assertions and made public, namely, ”time-related coverage, geographical coverage, technological coverage, precision, completeness. representativeness, consistency, reproducibility, sources of the data, and uncertainty of the information.” But this is as far as the guideline stretches, labelling it as a ”recommendation” rather than a ”requirement”, but also pitching little insight into how these are to be treated, if need be. The World Resources Institute in their Greenhouse Gas Protocol Report, the European Commission as part of their commission recommendation report for the reporting and communication of product environmental performance [34], and Edelen et al [35] in a technical report for the United States Environmental Protection Agency all attempted to address the issue at hand and each developed their own versions semi-quantitative data quality assessment framework. Sharing a majority of the quality indicators and respective scoring criteria in their respective scoring matrices, they have their pitfalls. For instance, the approach from [34] is purely qualitative in its scoring, is too ambiguous with the criteria per indicator, and calls for evaluation of the entire system at once that does not capture the situation upon communication for more complex systems; the commission recommendation [36] still leaves it upon system specifications and the practitioners’ judgement when scoring for time, technological and geographical representativeness; and the framework from Edelen et al, while presenting arguably the most robust and widely applicable version, is difficult to implement with distinct indicators for flows and processes coexisting in the setup.

3
Knowledge Gaps

As the influence of sustainability increases on steering upcoming technological developments, the need for a robust system to quantify these prospective benefits or limitations becomes increasingly important. The framework of life cycle assessment has evolved at accelerated rates within aerospace, but the state-of-the-art still has some glaring gaps. This project shall attempt to bridge the following.

3.1. Life Cycle Inventory Analysis - Data Availability, Collection and Quality Assessment

Other than the construction of the ecological profile of a given system, life cycle assessment studies also carry the responsibility of adding to the existing global knowledge base. This can be attributed to, among other aspects, the limited availability of representative data mirroring industrial practices. A majority of studies were observed to have to depend upon aggregated life cycle inventory databases and published articles even for processes foreground processes due to absence of infrastructure for data collection, intellectual property protection, or both. Moreover, little heed was paid to quality of the system being modelled, and that of the data being used as input to aggregate the inventory. The representativeness of the accumulated inventory used to compute the environmental impact of a certain system not only has a significant impact on the credibility of the objective outcomes, but also on the applicability of these results to comparable systems. Hence, it is almost impossible to find a robust, baseline impact for a given product from the various publications to verify the findings of a given study. To this end, each of the foreground processes within the scope of this project shall be modelled based on measured, qualified primary data, while highly characteristic secondary data shall be sourced for background processes. Moreover, all the systems shall be assessed for data quality, the scored matrices and final scores being communicated, adding industrially representative environmental profiles to the state-of-the-art as one of the major contributions.

3.2. Manufacturing Waste Processing - Burden/Benefit Allocation

Another aspect possessing an inherent ambiguity is that of burden and benefit allocation within a system. Methodological standards and guidelines discourage the practice of allocation when possible but with the technological advancements being made in the direction of achieving leaner production systems and circularity in economies, it is well on track to becoming an indispensable activity. To this end, this thesis shall also attempt to treat a co-product system to formulate, and apply a method to apportion the burdens and benefits among the product flows by means of models based on primary data collected for processing of consolidated thermoplastic composite waste as illustrated in the work of de Bruijn et al [29].

4
Research Questions

Coalescing the learnings from reviewing the state-of-the-art with the identified knowledge gaps, a case study shall be selected to be assessed for environmental impact over the different phases of its life cycle under the LCA framework with life cycle inventory data qualification. The primary research question has been formulated as:

"How would the quantitative environmental footprint of a wing rib compare over its product life cycle across five different material and manufacturing system scenarios, namely:

A: Aluminum Alloy 7050-T7651 products manufactured via Numerical Control Machining,

B1: Carbon Fiber-reinforced Epoxy products manufactured via Autoclave Curing,

B2: Carbon Fiber-reinforced Epoxy products manufactured via Resin Transfer Molding,

C1: Carbon Fiber-reinforced Polyetherketoneketone (PEKK) products manufactured via Autoclave Consolidation, and

C2: Carbon Fiber-reinforced Polyetherketoneketone (PEKK) products manufactured via Out-of-Autoclave Press Consolidation?"

The life cycle of a product can broadly be split into four phases; material production/extraction, product manufacturing, operational/use phase, followed finally by the end-of-life. This ecological footprint profile could be modelled under different frames of reference, including and/or excluding some of these phases. This practice of inclusion and exclusion informs the definition of what are termed as system boundaries and is known to have a large influence on the computed impact(s). Also, the overall resource investment in aggregating the life cycle inventory, i.e., the data quality for a given system has a large influence in the representativeness and applicability of the outcomes of the study. Hence, both aspects shall be treated as sub-questions, the answers to which shall eventually converge and address the overarching question.

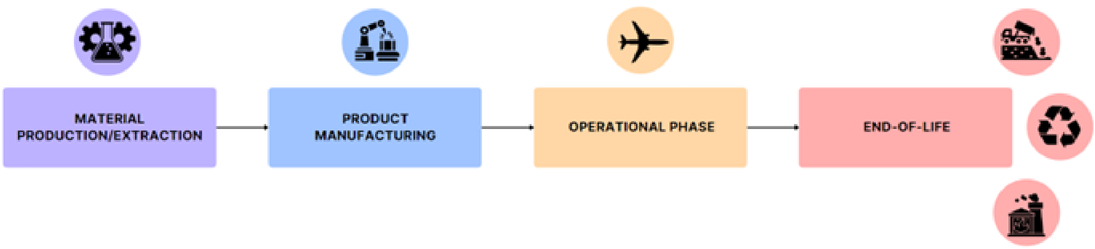

Figure 4.1: Phases of a generic product life cycle

SRQ 1: ***”How would the system scenarios (A, B1, B2, C1, and C2) fare if the analyses were to encompass only the cradle-to-gate phases?”***

SRQ 2: ***”How would the system scenarios (A, B1, B2, C1, and C2) compare if the cradle-to-gate analyses were extended to include the operational phase of the aircraft, i.e., cradle-to-end of service?”***

SRQ 3: ***”How can the the datasets being used as input to aggregate the respective inventories per scenario (A, B1, B2, C1, and C2) be qualified and communicated in a transparent, comprehensible and systematic fashion?”***

SRQ 4: ***“If waste stream processing, i.e. recycling and downcycling practices were included in the system boundaries, how would the environmental burdens and benefits be allocated between the main and secnodary product systems?”***

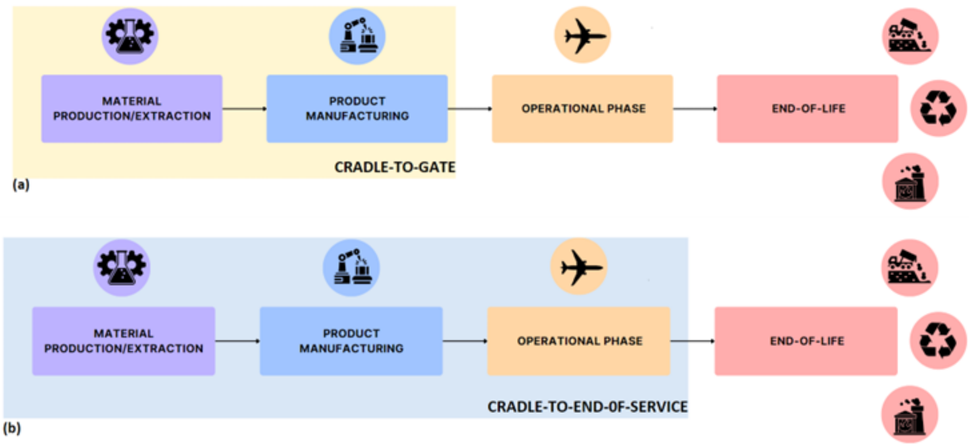

Figure 4.2: Phases of a product life cycle highlighted to treat the scopes of Sub-Research Questions 1 and 2 , respectively. (a) Cradle-to-gate and (b) Cradle-to-End of service

5 Methodology

This section details the approach followed through the course of this thesis and its relevance to the research objectives, beginning with the broad framework of LCA, subsequently zooming in on how aspects of data inventory aggregation and qualification, and allocation procedures taken up were treated. It is important to highlight that the practice of normalization was taken up to not only make the communication of results more comprehensible, but also protect intellectual property rights of the stakeholders without compromising on the quality of the output. Within the scope of life cycle assessment, normalization generally implies dividing the computed impact by that of reference situation. But for this project, the computed impacts were normalized to the scenario with highest per impact indicator.

5.1. Life Cycle Assessment – Procedure, Requirements and Guidelines

Two major standards, directives from the International Organization of Standardization (ISO 1404X:2006 series) [37] [33] and those from the European Commission (Product Environmental Footprint Guidelines) [36], were used as the baseline for setting up the foundation and direction of the analysis. Per the guidelines, the study was divided into four iterative phases:

1. **Goal and Scope Definition**: This phase describes the depth, breadth, and level of detail in reference to the subject and intended use of the study.
2. **Life Cycle Inventory Analysis**: Life cycle inventory is essentially an aggregated form of the input/output data with regards to the system under scrutiny. The effort and resources invested in the process of data collection are heavily influenced by the defined goals of the study.
3. **Life Cycle Impact Assessment**: Life cycle impact assessment makes use of characterization models to categorize and convert the raw inventory data to information of environmental significance.
4. **Life Cycle Interpretation**: Interpretation forms the basis for conclusions and recommendations derived from the results of the inventory analysis and impact assessment, in line with the goal, scope, assumptions, and limitations of the study.

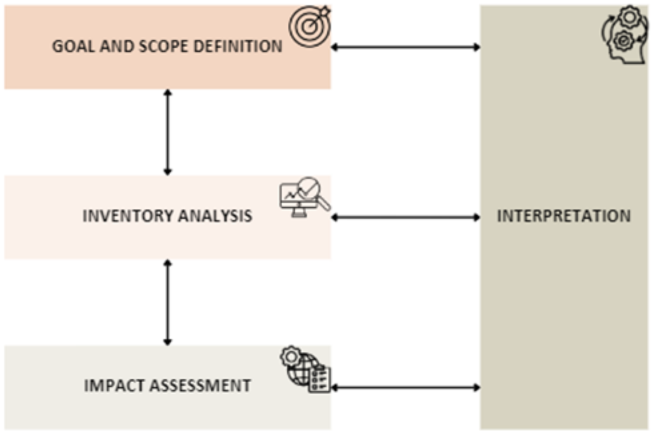

Figure 5.1: Stages of a life cycle assessment study based on ISO 1404X:2006 [33]

5.2. Life Cycle Assessment - Software Environment

Formerly known as GaBi©, LCA For Experts© software package provides a modelling environment for life cycle assessment accompanied by a life cycle inventory database containing good quality environmental data for a variety of material and processing systems. Through the license available on the networks of GKN Aerospace©, all the life cycle inventory aggregation, life cycle impact assessment and interpretation activities were carried out on this software environment. Furthermore, the environmental data for upstream, downstream, and other processes that are outside the influence of GKN Aerospace© were sourced predominantly from the Sphera Managed LCA Content 2023© database.

5.3. Life Cycle Inventory – Primary Data, Secondary Data, and Aggregation

Once the goal and scope of the study were defined, the data collection and aggregation were taken up. The process, as illustrated in Figure 5.2 in the form of a flow chart/decision tree, based on the recommendations per the ”Data Needs Matrix” in the Category Rules-Aircraft document [38], was followed for each of the system scenarios per life cycle phase. It is important to highlight that the data quality requirements per situation were adapted to the quality assessment framework being used as part of this project.

To contextualize the information in Figure 5.2, processes that the practitioner(s) or the practitioner(s)'s organization have direct access to, being product manufacturing practices at GKN Aerospace© for this project, fall under foreground systems and were modelled for based on primary, non-aggregated, high-quality data. Processes not run directly by the organization conducting the study, or background processes, holding high relevance, raw material production for this project, were either modelled on high quality data provided by the material supplier in an aggregated form, or a secondary, aggregated inventory was aggregated but replacing the flow parameters concerning electricity grid mixes, means of transport, and the transport distance to the most representative options. For background processes with little relevance, such as auxiliary material manufacturing for this project, were based on secondary, aggregated data of relatively lower quality.

5.4. Data Quality Assessment Framework

Drawing inspiration from the Product Environmental Footprint Guidelines [36], Greenhouse Gas Product Accounting Methodology [34], SETAC report [32], and Edelen et al [35], a novel semi-quantitative data quality assessment was conceptualized and applied within this project. Five quality indicators were deemed pertinent, described in the following subsections.

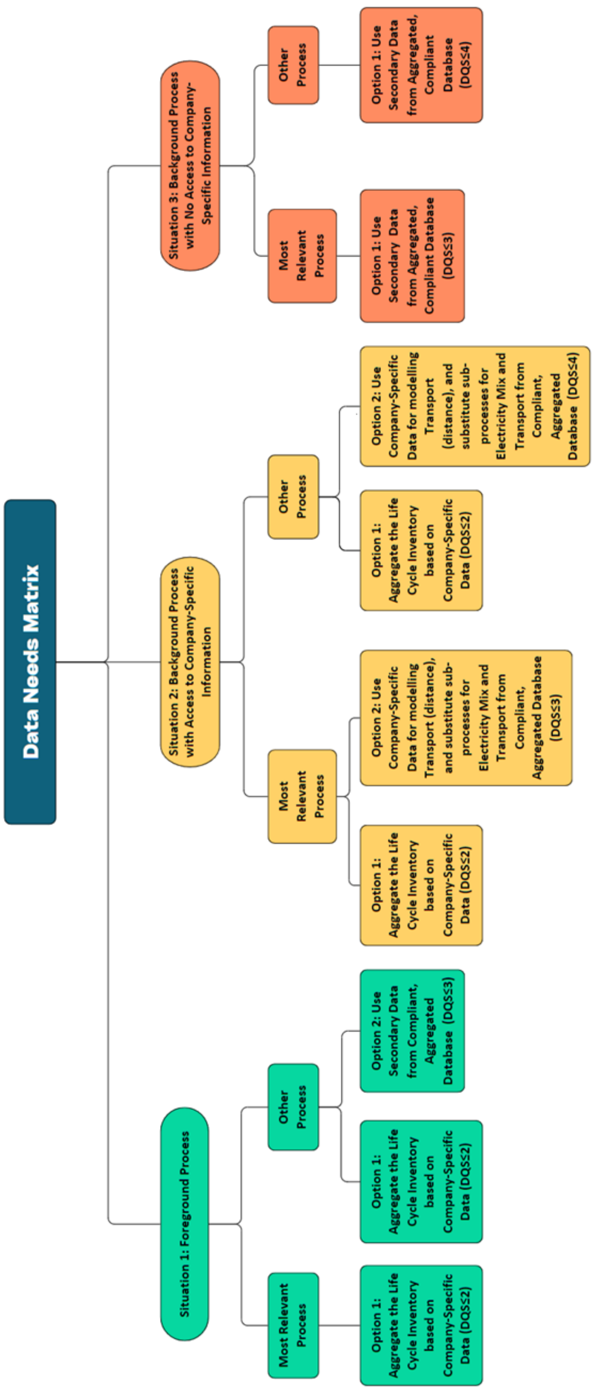

Figure 5.2: Data needs decision flow for life cycle inventory aggregation based on the recommendations from Product Environmental Footprint Category Rules - Aircraft [39]

5.4.1. Temporal Representativeness (TR)

Temporal representativeness intended to capture the age of the dataset in relation to its representativeness at the time of conduction of the study since older data may not optimally reflect the ecological ramifications of the technology(/ies) being scrutinized.

5.4.2. Geographical Representativeness (GR)

Geographical representativeness intended to capture data quality in relation to the geographic specificity. Ideally, all the data should be site-specific for the process but due to gaps in availability, averaged data from existing datasets may be used. This decrease in resolution would be reflect in a worse score.

5.4.3. Reliability (R)

Flow reliability was meant to qualify the dataset based on the nature of source(s) of derivation of the data. This might, on some level, be indicative of the behaviour of the probability distribution curve of the data as well. Although not always the case, a better score could be a sign of low uncertainty, or high precision. Data may be collected at the production sites associated with specific unit processes or product flows within the system boundary, calculated (energy-balance, stoichiometric, etc.), estimated based on similar, existing datasets or obtained from literature (may or may not state whether values were measured, calculated, or estimated). Although it is ideal to have a dataset consisting only up-to-date, real-time measurements, in practice, the data may include a mixture of the following, in descending order of preference;

1. Measured
2. Calculated
3. Estimated

5.4.4. Technological Representativeness (TeR)

'Technology' was broken down further into constituent aspects, namely, process design, process operational parameters, process scale and material grade specificity. A fully primary dataset is the ideal situation with a complete overlap from all aspects. In case of secondary data being used, the following applied;

- Process Design was to assess the degree of overlap between the process at the source of the data and the process under assessment in terms of material, product and energy flows. System-level flow diagrams from the source and the study being conducted being communicated (when possible) and compared to qualitatively determine an acceptable extent of overlap.
- Process Operational Parameters include, but are not limited to, temperature, pressure, production rates, etc. The practitioner(s) was required to communicate (when possible) and compare these conditions for the source and those for the system process in the study being conducted to determine the extent of overlap.
- As the name suggests, material grade specificity was to factor in the similarity in relevant properties of the material being used in the source dataset and in the study being conducted. The keyword being "relevant", only the assessment and comparison of processing conditions, raw material usage, ancillary material usage, etc. being imperative and not properties such the mechanical or chemical behaviour.
- Scale intended to verify if the dataset being used was appropriate for the technology under scrutiny from the perspective of product series and equipment state used for measuring, calculating, or estimating the data. If there was any estimation or calculation going in the scale up or down directions, this aspect was deemed to have lost value.

5.4.5. Completeness

Completeness was meant to account for the proportion of flows and unit processes that have been included in the scope of the analysis, with regards to the defined system boundaries. It is of course reasonable to exclude some inputs, owing to issues with data availability, being deemed unimportant as a result of sensitivity analyses or high cost of data acquisition relative to significance.

$$CompletenessFraction = \frac{Number of flows and processes included in the system boundary}{Total number of flows and processes that make up the product system} \quad (5.1)$$

The fraction above was implemented without any underlying weighting on importance of certain flows/processes over others. The scoring matrix hence allows some relaxation to stay within reach of the best score possible.

5.4.6. Data Quality Assessment - Scoring Matrix and Score Calculations

Inventories for each of the systems were a combination of primary data for flows building up the respective process data, and aggregated process datasets sourced from the datasets part of the Sphera Managed LCA Content 2023©. The data on the flows were scored per the flow-level indicators, the same being averaged to obtain the score for the respective primary process for these indicators, while process-level indicator scores were assigned directly. For aggregated process data, the scores were assigned directly, per the guidance provided in Table 5.1.

PROCESS-LEVEL INDICATORS
FLOW-LEVEL INDICATORS

	1	2	3	4	5
TEMPORAL REPRESENTATIVENESS (TR) *	Less than 3 years of difference	3 to 6 years of difference	6 to 10 years of difference	10 to 15 years of difference	More than 15 years of difference OR Age of data unknown
GEOGRAPHICAL REPRESENTATIVENESS (GR)	Site-specific data	Province/City average OR National average	Sub-region average	Continental average	Global data
RELIABILITY (R)	Verified** data based on measurements	Non-verified data based on measurements OR Verified data based on calculations	Non-verified data based on calculations OR Data from literature or established LCI databases (Ecoinvent, GaBi, Granta, etc.)	Estimates based on calculations/existing data OR Non-verified data from literature	Rough estimate not based on calculations, and/or having known defects
TECHNOLOGICAL REPRESENTATIVENESS (TeR) ***	All aspects are covered well	Three of the aspects covered well	Two of the aspects covered well	One of the aspects covered well	None of the aspects covered well
COMPLETENESS (C) ****	CF ≥ 0.8	0.6 ≤ CF < 0.8	0.4 ≤ CF < 0.6	0.2 ≤ CF < 0.4	CF < 0.2

* Difference here refers to the time between when the dataset was generated, calculated or estimated and when the study is being conducted.
** Verification could be carried out via internal/external on-site audits, mass-balance calculations, stoichiometric calculations, etc.
*** The aspects to be covered are Process Design, Process Operating Conditions, Material Grade Specificity and Process Scale.
**** Completeness Fraction, CF = (Number of determined flows and/or processes included in the system boundary) ÷ (Total number of determined flows and/or processes that make up the product system)

Table 5.1: Life cycle inventory - Data quality assessment scoring matrix

The assessment for each of the indicators was conducted at the smallest scale possible, be it a flow, a unit process, or aggregated system processes, and their cumulative mean computed to obtain the final score for that respective indicator. These were illustrated by means of spider charts. Also, the scores per indicator were used as input for the following equation to obtain the overall data quality score (DQS) for the dataset used.

$$OverallDataQualityScore = \frac{TR + GR + R + TeR + c}{5} \tag{5.2}$$

Based on the overall DQS, grades were assigned to certain ranges as in Table 5.2, per the guidance from PEF[36] and [38]. While for objective systems, the lowest possible score was strived towards, looking at the study through a comparative lens, it was deemed ideal to have datasets lie in the same quality grade, while aiming for the lowest respective scores, to make for a level playing field.

OVERALL DATA QUALITY SCORE (DQS)	OVERALL DATA QUALITY GRADE
DQS ≤ 1.6	Excellent
1.6 < DQS ≤ 2.0	Very good
2.0 < DQS ≤ 3.0	Good
3.0 < DQS ≤ 4.0	Fair
DQS > 4.0	Poor

Table 5.2: Life cycle inventory - Data quality score grading matrix [36]

5.5. Burden/Benefit Allocation - Circular Footprint Formula

One of many reasons for high performance thermoplastic composites to have drawn interest from the aerospace industry, also applicable to metal alloys to a great extent, is the prospect of recycling/downcycling. Although still nascent in the aspects of product quality and traceability for the composite class, two very relevant issues within the discipline, it is more than reasonable to evaluate the environmental viability of these practices. Hence, within the scope of this project, high quality, primary data was collected, aggregated and brought into the system boundaries for the processing the manufacturing waste for consolidated thermoplastic composite waste. To perform the distribution of the burden of the added activity in combination with the benefit of virgin material being produced, an approach inspired heavily by the circular footprint method developed as part of initiatives from the European Commission was implemented. The circular footprint method facilitates for the balance between the supply and demand for recycled material to be taken into account, in addition to incentivizing safeguarding the quality of material post waste-processing. The results were then incorporated via a co-product scenario, a non-load-bearing structure with an assumed weight, being manufactured using the aforementioned manufacturing waste and that via industry-standard virgin materials.

$$E_{Material} = (1-R_1).\,E_{virgin} + (A.\,E_{recycling} + (1-A).\,E_{virgin}.\,\frac{Q_{S_{input}}}{Q_{virgin}}) + (1-A).\,R_2.\,(E^*_{recycling} - E^*_{virgin}.\,\frac{Q_{S_{output}}}{Q^*_{virgin}}) \tag{5.3}$$

Where,

A: Allocation factor determining the proportion of burden and benefit between the supplier and consumer of the processed waste.

R_1: Proportion of secondary/recycled material at input.

E_{virgin}: Impact element quantified per functional unit associated with the acquisition and production of virgin raw material.

$E_{recycling}$: Impact element quantified per functional unit associated with the recycling activities for secondary/recycled material at input.

$Q_{S_{input}}$: Quantified quality of the secondary/recycled material at input.

Q_{virgin}: Quantified quality of virgin material at input.

R_2: Proportion of secondary/recycled material supplied to the co-product system.

$E^*_{recycling}$: Impact element quantified per functional unit associated with the recycling activities for secondary/recycled material supplied to co-product system.

E^*_{virgin}: Impact element quantified per functional unit associated with the acquisition and production of virgin raw material assumed to be substituted at the co-product by recycled/secondary material.

$Q_{S_{output}}$: Quantified quality of secondary/recycled material supplied to the co-product system

Q^*_{virgin}: Quantified quality of virgin material assumed to be substituted at the co-product by recycled/secondary material.

Part II

Life Cycle Assessment

6 Goal and Scope Definition

This section describes the process of case study selection before establishing the goal and scope of the study undertaken, reiterating that the specific aspects to follow are derived from the ISO 14044:2006 series [33], [37] and the PEF Guidelines [36].

6.1. Case Study Selection

The case study component selection bore the following aspects in mind:

- The component must be a ”typical product”, aligning closely with the related work packages within the broader scope of the Mobility Fund for the results to be more transferable and representative.
- Alternate designs, material systems and manufacturing systems must also applicable to the product system to have the comparison mirror reality more closely.
- The data on these alternate options must be available with relative ease, preferably in the open source knowledge-base to facilitate aggregation of a high quality life cycle inventory.

A ***Wing Rib*** was hence deemed to be a suitable product having evolved over the past decades in design, material and manufacturing techniques. The component specifications were modelled based on a demonstrator product being developed at GKN Aerospace© as shown in Figure 6.1. It is important to highlight that the ”gross product” served as the blueprint for the pre-trimming product for the composite material-based scenarios B1, B2, C1, and C2, while the ”final product” served as that for modelling the product-at-gate for all the scenarios.

6.2. Goal Definition

- *The intended application:* Analyzing the influence of Thermoplastic Composite Technology on Sustainability in Aviation.
- *Reason to carry out the study:* Being conducted as a Master Thesis Project in an effort to obtain an MSc in Aerospace Engineering at the Faculty of Aerospace Engineering at TU Delft. The study also aligns with the efforts of GKN Aerospace©, and their involvement and contribution towards Work Package 4.5 of the *Mobility Fund: Thermoplastic Material for Sustainable Aviation.*
- *Intended Audience:* Life cycle assessment practitioners or other interested stakeholders, with a specific interest in relative impacts for aerospace material and manufacturing systems. The report shall be available as an open source document as part of the TU Delft Repository for Master Theses.
- *Comparative Assertions (if any):* Comparisons shall be drawn between five scenarios, namely, Aluminium 7050 series manufactured via Numerical Machining, Carbon Fiber-reinforced Epoxy manufactured via Autoclave Curing and Resin Transfer Molding, and Carbon Fiber-reinforced Polyetherketoneketone (PEKK) manufactured via Autoclave Consolidation and Out-of-Autoclave Press Consolidation with the case study of a Wing Rib. The restatement and use of the computed impacts for other applications must be mindful of the assumptions and limitations of this study.

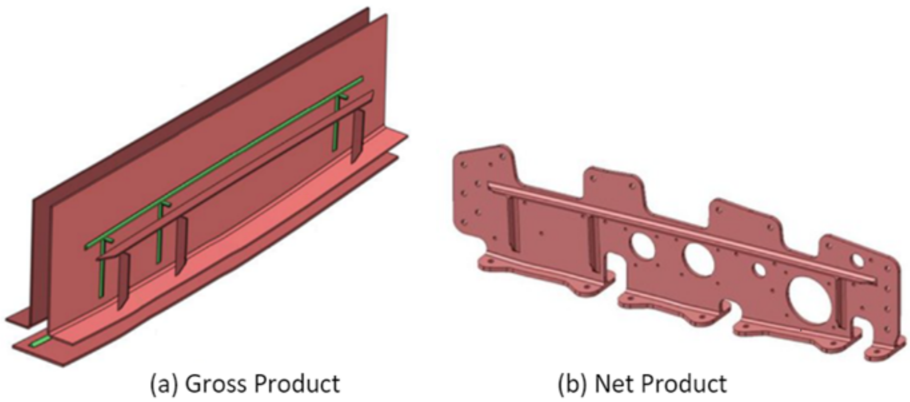

Figure 6.1: Illustration of the case study component - wing rib [17] (a) Gross product - precursor to laminate trimming (b) Net product - product at gate [17]

6.3. Scope Definition

- *Function(s) of the Product System(s):* The product system is a Wing Rib. The primary functions are to impart the required shape and geometry to the wing while providing structural support to the skin-stringer combination.
- *Functional Unit:* One wing rib, responsible for bearing structural loads for a life cycle of a a single-aisle, narrow body aircraft for a service life period of 22.9 years, averaging 1455 flight cycles per year, covering 1452 km per cycle [38].
- *System Boundary Definition:* Cradle-to-gate and cradle-to-end of service systems were consecutively modelled for the scenarios under scrutiny, neglecting the treatment of manufacturing and end-of-life waste streams. Relevant flows were captured for the respective material production, the manufacturing and operational phases for each of the alternatives. The specific information with regards to inclusions and exclusions of flows and processes can be found in Chapter 7.
- *Life Cycle Impact Assessment Methodology to be used:* Environmental Footprint (EF) 3.0, based on the recommendations of the European Commission [36].

An inherent uncertainty exists with regards to the design of the rib, and eventually of the overall wing box, in relation to the material system. The total number of ribs required, spar placement, and mechanical and chemical interaction between different materials at structural interfaces are all factors that are influenced by the constituent structural members of the wing, and it was hence not deemed viable to compute the expected weight-saving with the inclusion of composite members with the amount of information that was available. Therefore, each of the systemic scenarios was assumed to produce products with identical masses as drop-in substitutes for one another.

7
Life Cycle Inventory Analysis

With the product system, the goal and scope of the study defined, the subsequent step was to aggregate the life cycle inventory for the respective scenarios. Acknowledging the span of the systems under scrutiny, the following subsections delineate their properties in the modelled state beginning with the details of the operational phase model with regards to the aircraft type, fuel system and related emission factors, and the baseline scenario models feeding into the system boundary charts.

It is important to highlight that *infrastructural and industrial facilities* such as tooling/mould manufacturing, air conditioning for work spaces, computer hardware systems, etc. setting up the working environment, *supply chain oriented transport systems* such as material transport between facilities (other than the exception of raw material transport to manufacturing facility), *non-destructive inspection* of products at gate, *waste stream processing*, and *maintenance operations* for the fleet in service, and end-of-life waste treatment were cut-off from the system.

7.1. Process Flow Charts and System Boundary Definition

Process flow charts are useful tools for visualising the complex sequences of inputs and actions that make up a system's or product's life cycle. From the extraction of raw materials to manufacturing, distribution, usage, and disposal, these charts outline each step. Stakeholders can have a better understanding of the relationships and links across the life cycle by receiving a concise yet complete summary of the processes. In order to implement targeted improvements, it is imperative to identify hotpots in the modelled system, i.e., flows or processes that have a significant contribution to the overall environmental impact. Moreover, transparent communication of a well defined system, including the boundaries, not only facilitates a better understanding of the results in context of the scope, but also reduces ambiguity in the methodological choices taken up, hence improving reproducibility. The flow charts have been colour coded for the reader to be able to make the distinction between the various life cycle phases per scenario, the highlighted region describing the outer boundaries.

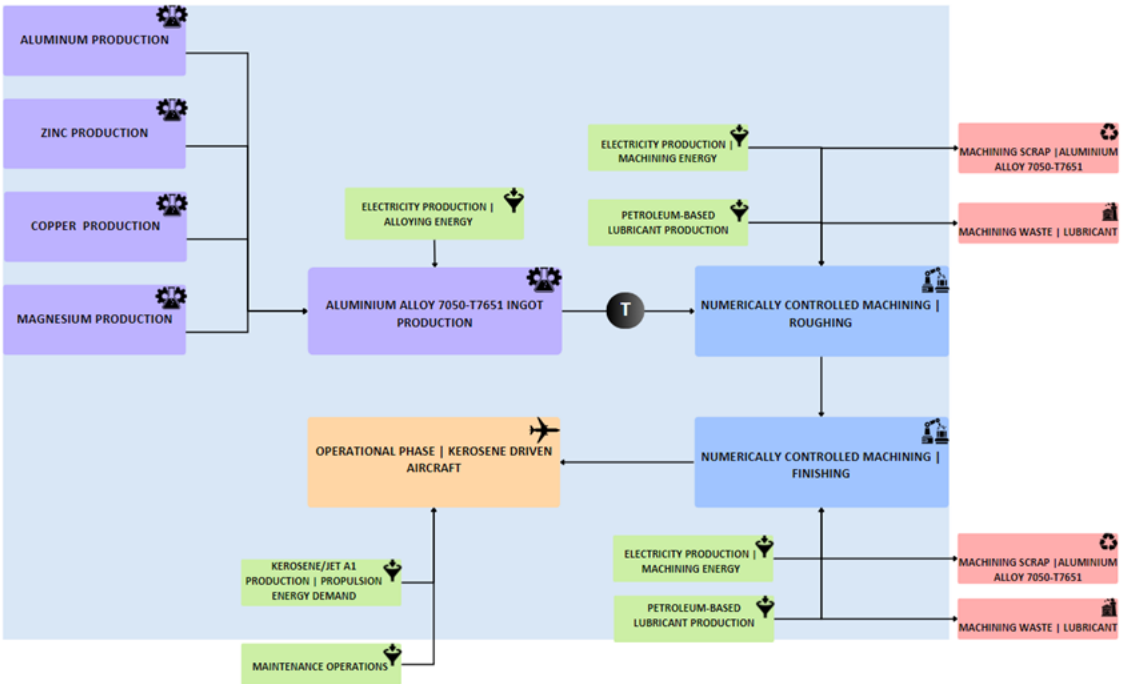

Figure 7.1: Process flow of the modelled numerically machined aluminium alloy 7050-T7651 product life cycle

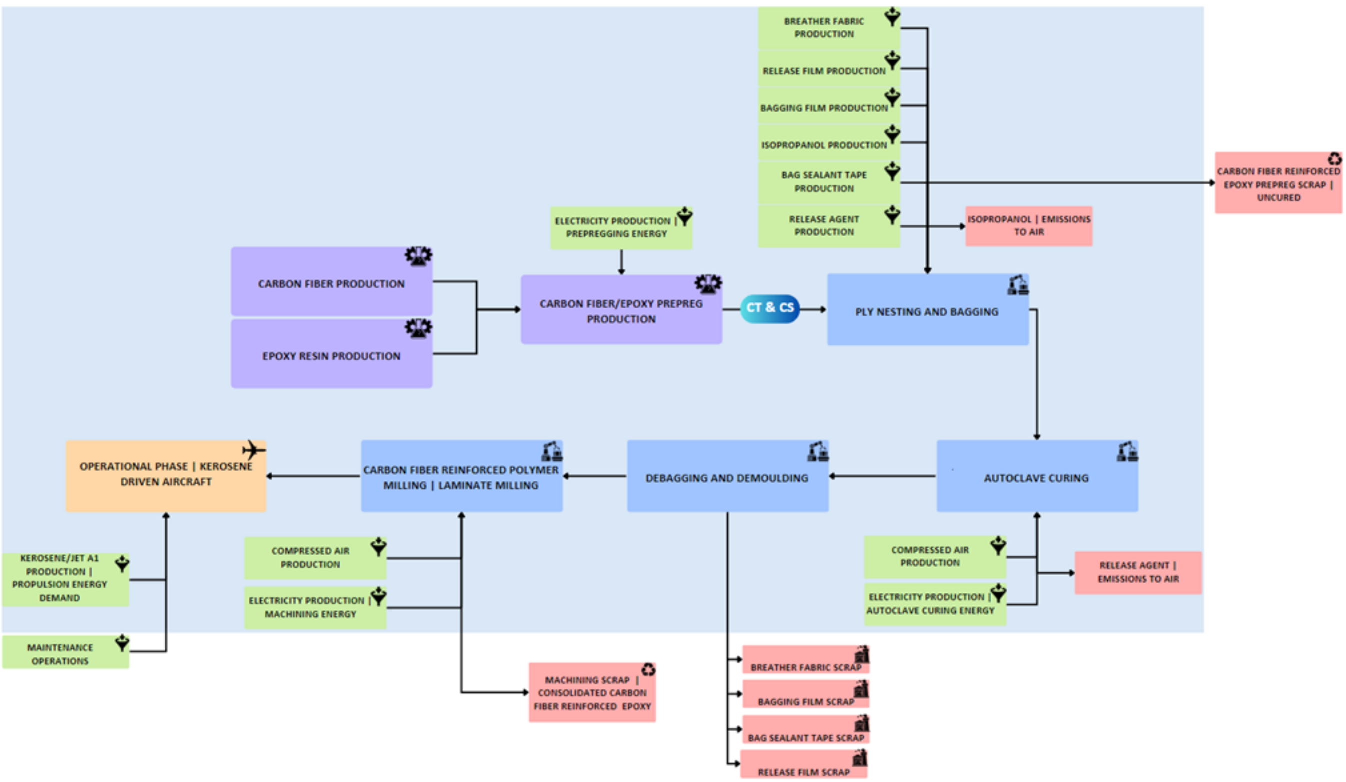

Figure 7.2: Process flow of the modelled autoclave cured carbon fiber reinforced epoxy product life cycle

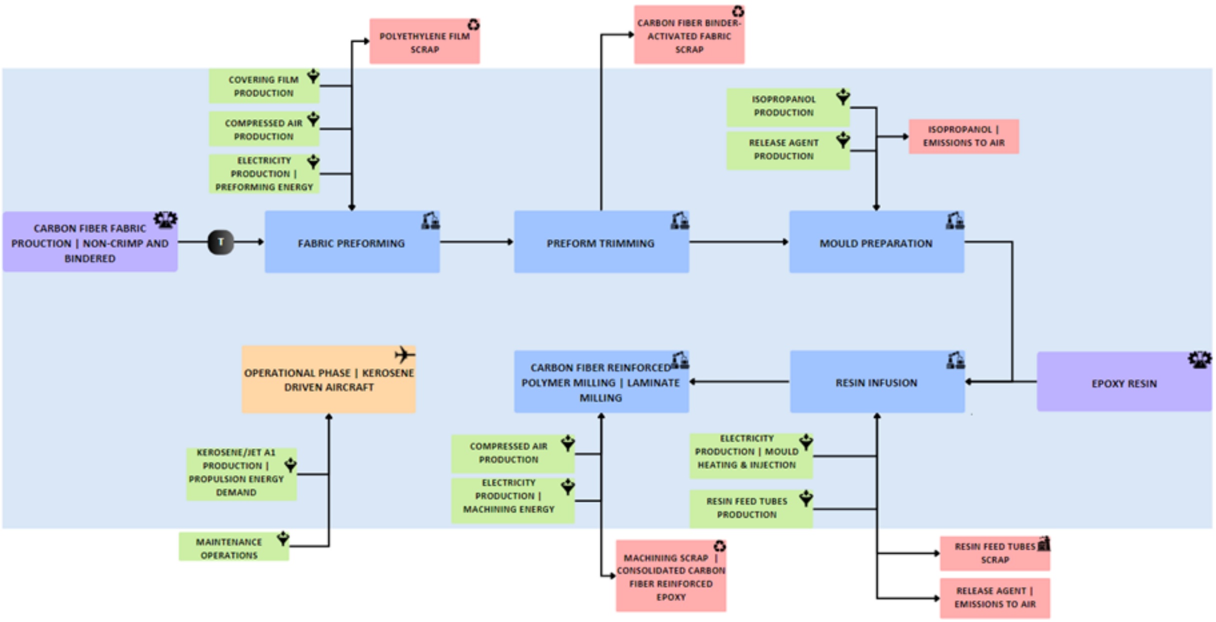

Figure 7.3: Process flow of the modelled resin transfer molded carbon fiber reinforced epoxy product life cycle

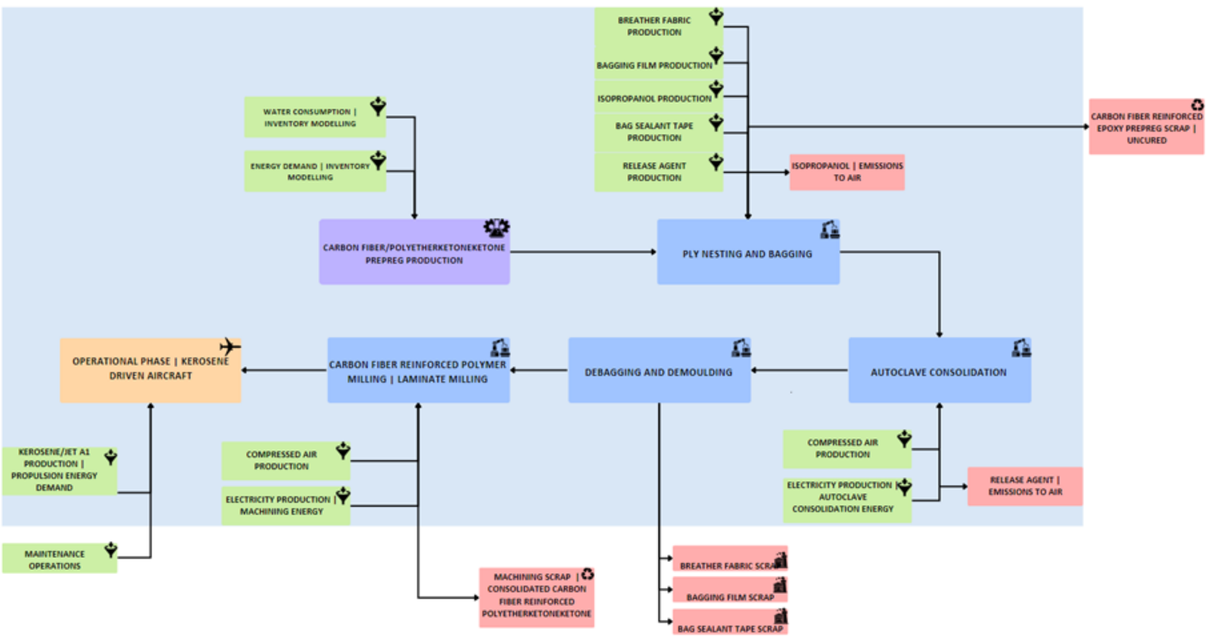

Figure 7.4: Process flow of the modelled autoclave consolidated carbon fiber reinforced PEKK product life cycle

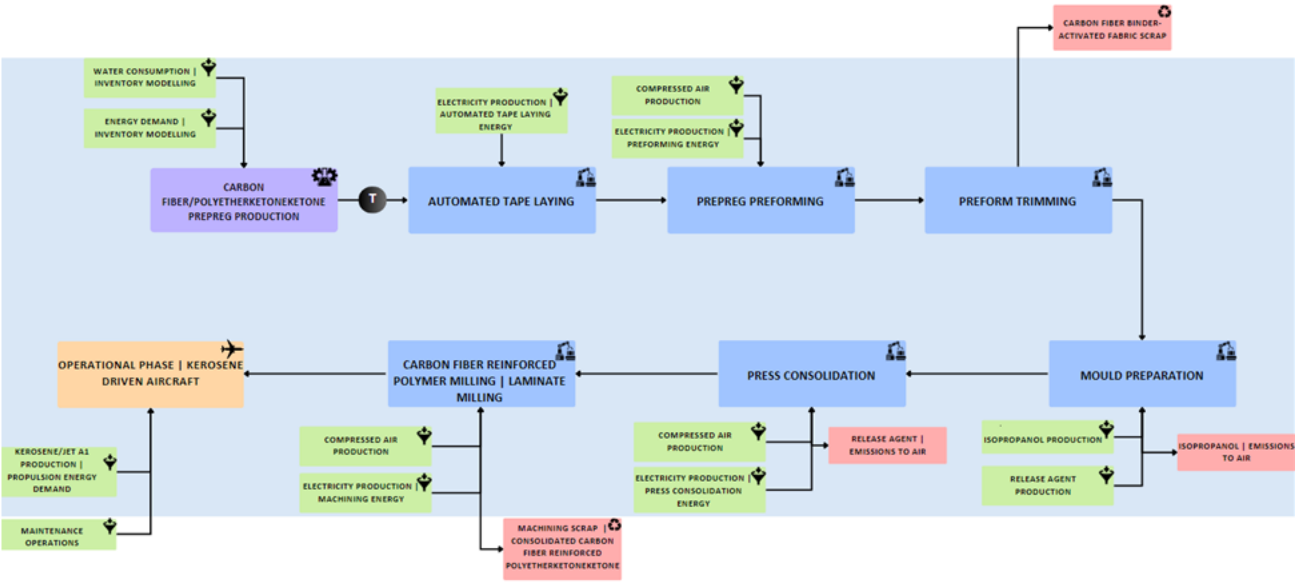

Figure 7.5: Process flow of the modelled press consolidated carbon fiber reinforced PEKK product life cycle

7.2. Kerosene Production and Combustion over Aircraft Service Life

The use-phase of the aircraft was modelled based on the recommendations from the Product Environmental Footprint Category Rules for Aircraft for a ”narrow body, single-aisle aircraft”. Magnifying further for take-off and payload weight modelling, an Airbus©A320 was used as the baseline for these computations, values being sourced from the manufacturer’s resources [40]. As for the fuel demand and emissions due to fuel burn, these were modelled based on the process dataset “Cargo plane, 22 t payload, technology mix, kerosene driven” in the Sphera Managed LCA Content, 2023 representing global applications. As highlighted before, different material systems for the wing rib would affect the design of the rib itself and eventually, the overall structure of the wing box, the uncertainties to this are too large to be modelled in current scope. Hence, it was assumed that each of the product scenarios results in a drop-in product on the existing fleet of the Airbus©A320 wing box. The operational phase model attempts to generate an ecological impact profile specific to the mass of an aircraft component and hence, assist with the sensitivity analyses, responsible for accounting for prospective lightweighting opportunities the ensue, while also providing some insight into the contribution of this life cycle phase when weighed against the rest.

KEROSENE COMBUSTION EMISSION PROFILE	
Methane (g/kg)	0.04
Carbon Monoxide (g/kg)	0.92
Carbon Dioxide (g/kg)	3150
Water Vapour (g/kg)	1240
Nitrous Oxide (g/kg)	0.15
Non-Methane Volatile Organic Compounds (g/kg)	0.14
Nitrogen Oxide (g/kg)	14.33
Particulate Matter	0.0175
Sulphur Content-Kerosene (ppm)	480
Sulphur (g/kg)	0.96

Table 7.1: Specific emission profile of kerosene combustion modelled during aircraft operations

OPERATIONAL PHASE PARAMETERS	
Service Life (Years)	22.9
Average Flight Distance (km)	1452
Number of Flights (per year)	1455
Take-off Mass (kg)	88200
Maximum Payload Mass (kg)	22000
Average Utilization Factor	0.834

Table 7.2: Parameters for the modelled service life of the aircraft [38]

7.3. Raw Material - Transport and Storage

For purpose life cycle assessment studies, modelling for intermediate transportation steps and storage requires a complete, optimized supply chain model. Unfortunately, this data is rather difficult to muster for a prospective study with multiple material/manufacturing systems, hence possessing an inherent uncertainty. Hence, this was only brought into the system from the perspective of a difference analysis, to quantify and illustrate the contribution of cooled transport and storage required for thermoset composite prepreg as opposed to the rest of the scenarios free from this constraint. Hence, in consultation with responsible colleagues within GKN Aerospace©, a baseline dummy distance of 100 km was used for the distance of raw material transport across scenarios, simulating conditions of raw material being sourced from a supplier within the Netherlands, the impact associated being computed as a mass-specific profile for cargo transport via a truck-trailer with a maximum payload capacity of 5000kg. As for storage, since the only intention was to model from the perspective of difference analysis, a hypothetical cooled storage was modelled for. The room was assumed to store 100kg of prepreg, and the characterized impact was scaled linearly to the mass required for the product under scrutiny.

COOLED STORAGE FOR CARBON FIBER REINFORCED EPOXY PREPREG	
Storage Temperature (°C)	-18
Average Ambient Temperature (°C)	28
Dimensions of Storage Room {LxHxB} (m)	2 x 2 x 2
Total Volume of Storage Unit (m^3)	8
Insulation Panel Material	Extruded Polystyrene
Insulation Panel Thickness (mm)	100
Duration of Storage (days)	14

Table 7.3: Parameters of the cooled storage space modelled for carbon fiber reinforced epoxy prepreg

7.4. Material Grade Specificity

7.4.1. Aluminium Alloy 7050-T7651

The specific alloy grade was selected in consultation with process experts within GKN Aerospace©, representative of the state of the in-service narrow-body, single aisle aircraft.The material composition and embodied energy were modelled based on the data sourced from Ansys Granta 2022 R1©, assumed to have no secondary/reprocessed metal inputs at this stage. Table 7.4 lists the percentage composition by mass for the various constituent metals. It is important to spotlight at this stage that the highlighted make for about 99.75% of the total by weight and the production of the rest of the constituents was hence cut-off expecting negligible impact contributions.

CONSTITUENT METALS	CONTENT BY MASS (%)
Aluminium	88.85
Zinc	6.20
Magnesium	2.30
Copper	2.30
Zirconium	0.12
Iron	0.07
Silicon	0.06
Titanium	0.03
Chromium	0.02

Table 7.4: Aluminium alloy 7050-T7651 - Composition by weight of the modelled alloy

7.4.2. Carbon Fiber

The fabrication of carbon fiber was modelled based on the pre-existing data in the Sphera Managed LCA Content, 2023 for common industry practices reflecting the production in Japan. The modelled environmental profile served as the input to prepreg production for scenario B1, and that for fabric production in scenario B2. It is important to highlight at this stage that the transportation of this substrate to the aforementioned downstream processing activities, i.e. prepreg manufacturing site and fabric production was left out of system boundaries for the respective scenarios.

7.4.3. Epoxy Resin

The production of the epoxy resin (synthesised via Bisphenol A and epichlorohydrin) was modelled based on the pre-existing data in the Sphera Managed LCA Content, 2023, representing the main technologies and import statistics for the synthesis in Germany. The environmental impact profile was fed as an input to prepreg production for scenario B1 in addition to being an input for scenario B2 as the injected matrix. The downstream transportation of the raw material for the prepregging operation was cut off system boundaries for scenario B1.

7.4.4. Bindered, Woven Fabric Production - Carbon Fiber

The production of the carbon fiber woven fabric was modelled based on the pre-existing data for "Carbon fiber fabric (250g/m²; bindered); Fiber areal weight: 250 g/m²; 5% epoxy binder" in the Sphera Managed LCA Content, 2023, stated to represent fabric production in Germany and Austria.

7.4.5. Prepreg Production - Carbon Fiber reinforced Epoxy

For the production of epoxy pre-impregnated unidirectional carbon fiber, the energy demand was the only input with conveniently accessible data, sourced from the Ansys Granta 2022 R1 platform, based on "Carbon fibers, high strength (5 micron, f) – Processing energy, CO2 footprint & water". The process of prepregging was assumed to take place in the Netherlands and was hence modelled for with the dutch average electricity consumption grid mix sourced from the Sphera Managed LCA Content, 2023.

7.4.6. Prepreg Production - Carbon Fiber reinforced PEKK

Exercising the option of contacting the material supplier, a full environmental profile of the pre-impregnated material was procured and translated into the required inventory format. To expound further, the material supplier had some internal standards of conduction of life cycle assessment studies, which incidentally happened to be a combination of a variety of impact assessment and characterisation methodologies different to the ones being used in the scope of this study. Hence, these impacts were converted into the Environmental Footprint 3.0 format by means of certain conversion factors as recommended by [36]. It is important to highlight that the work cited surveyed several studies in the process of computing these factors, but the applications were limited to civil and construction engineering. Hence, it was ensured that the correlation factors for the impact indicators were high enough to instil confidence in the environmental profile constructed post conversion. The conversion factors and the respective correlation factors for the respective indicator classes were sourced from [41].

7.5. Manufacturing Routes

7.5.1. Computer Numerically Controlled Machining

Computer Numerical Controlled (CNC) Milling progressively removes material from a substrate (billet) to obtain the final product shape employing multi-point cutting tools. The process was modelled to be executed in two broad steps, roughing, wherein larger cutting tools are used to remove a larger chunk of material rather quickly to obtain a gross form, followed by finishing, wielding smaller, high precision tools to achieve the desired geometry as well surface finish/quality. The data with regards to the buy-to-fly ratios, and the amount of material removed per stage was calculated based on primary data for a comparable product manufactured at GKN Aerospace©'s Global Technology Centre, Filton, England.

7.5.2. Autoclave Processing

This is a collective term for a series of processes preceding and including curing for thermosets, and conoslidation for thermoplastic composites in the autoclave chamber. This begins with the ply nesting step that entails laying the large prepreg rolls/sheets into the required geometry and stacking them layer over layer based in defined orientations on the mould. This prepreg stack is then prepared for vacuum bagging, covering first with a release film (not required in the setup for thermoplastic composites), followed by a breather cloth and finally with a bagging film. Air is evacuated from the bagged setup, and it is then heated and compressed under controlled conditions for stipulated times based on the process-specific recipe. Figure 7.6 is a simplified illustration of the said system. The gross product is then milled to obtain the final product geometry.

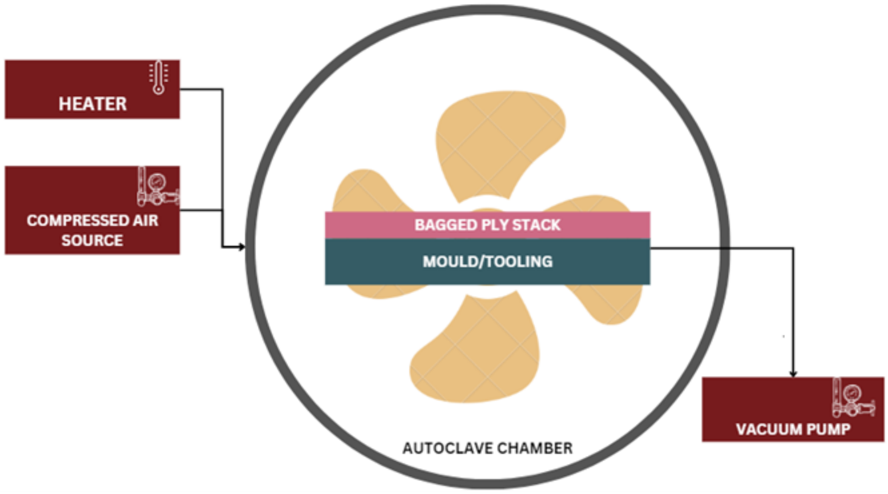

Figure 7.6: Simplified illustration of an autoclave cycle constituting a bagged laminate and tooling in the chamber

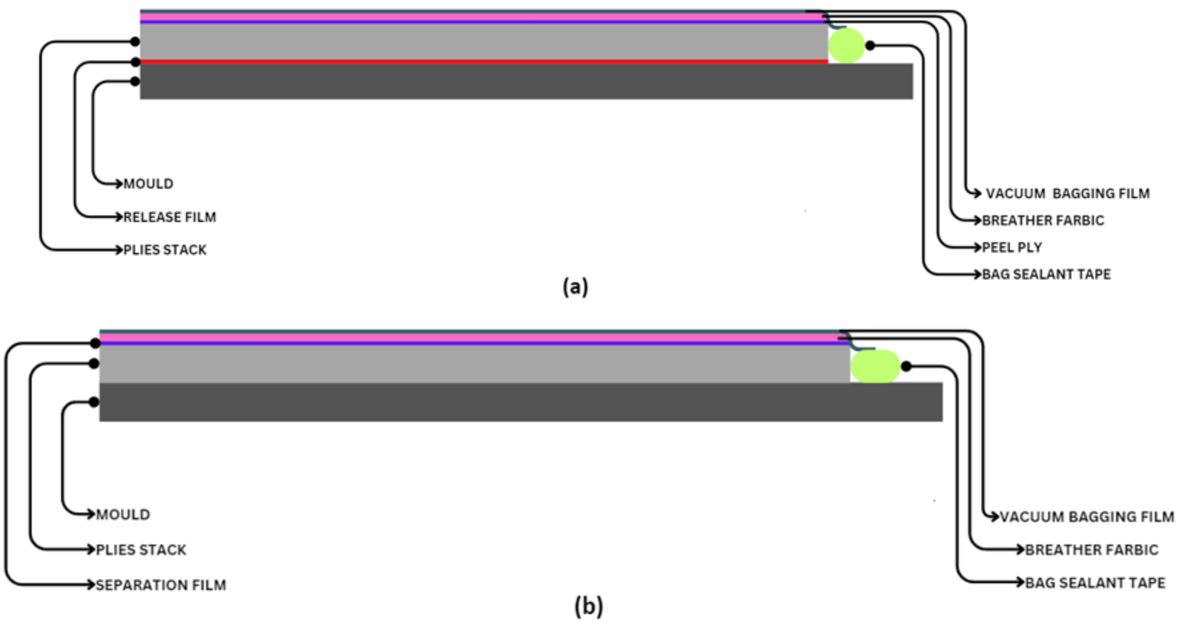

Figure 7.7: Simplified illustrations of the buildup over the course of laminate preparation for (a) fiber reinforced thermoset composites, and (b) fiber reinforced thermoplastic composites

The waste percentages for ply nesting and product trimming were estimated based on inputs from process experts, the production of auxiliary materials was modelled based on specific grades, their amounts calculated from areal estimations of the product, and the energy and compressed air demand were based on primary data measured at GKN Aerospace©'s Global Technology Center, Hoogeveen, Netherlands. An interesting fact here is that since the processing of fiber reinforced PEKK composites happens at temperatures significantly higher than those for epoxy-based composites, the auxiliary materials and laminate preparation steps were notably different.

AUTOCLAVE CHAMBER VOLUME (m^3)	4.7
PRODUCTS MANUFACTURED PER CHARGE	2
CURE CYCLE PARAMETERS	
Dwell Temperature (˚C)	180
Compaction Pressure (bar)	7
Dwell Duration (minutes)	120
AUXILIARY MATERIALS	
Cleaning Agent	Isopropanol
Release Agent	Solvent-Based Release Agent
Release Film	Polyvinyl Fluoride Film
Bag Sealant Tape	Butyl Rubber Tape
Peel Ply	Polyvinyl Fluoride Film
Breather Cloth	Glass Fiber Fabric
Bagging Film	Polyamide 6,6 Film

Table 7.5: Summary of the baseline process modelled for autoclave curing [42]

AUTOCLAVE CHAMBER VOLUME (m^3)	4.7
PRODUCTS MANUFACTURED PER CHARGE	2
CONSOLIDATION CYCLE PARAMETERS	
Dwell Temperature (˚C)	375
Compaction Pressure (bar)	7
Dwell Duration (minutes)	20
AUXILIARY MATERIALS	
Cleaning Agent	Isopropanol
Release Agent	Solvent-Based Release Agent
Bag Sealant Tape	Silicone Sealing Tape
Breather Cloth	Glass Fiber Fabric
Bagging Film	Polyimide Film

Table 7.6: Parameters of the process modelled for autoclave consolidation [43]

7.5.3. Resin Transfer Molding

Resin transfer molding, as opposed to autoclave curing, utilizes a fabric as input as opposed to autoclave curing. Hence, here the bindered fabric is trimmed and nested based on the required geometry. A preforming step heats the stack up to a suitable temperature to activate the binder material and then compacted under a cold mould to ensure some adhesion between the layers and impart a gross product shape to the stack. This is followed by placement of this stack in a mould that is heated to the processing temperature of the epoxy resin, the resin injected under suitable pressure and viscosity conditions, the tool closed for the curing reaction to occur, and cooled to room temperature before demoulding. Figure 7.8 is a simplified illustration of the said system. The gross product is then trimmed to obtain the net product geometry.

PRODUCTS MANUFACTURED PER CHARGE	1
CURE CYCLE PARAMETERS	
Cure Temperature (°C)	180
Injection Pressure (bar)	3
Dwell Duration (minutes)	120
AUXILIARY MATERIALS	
Cleaning Agent	Isopropanol
Release Agent	Solvent-Based Release Agent
Resin Feed Tubes	High-Density Polyethylene Tube
Breather Cloth	Glass Fiber Fabric
Bagging Film (at Preforming)	Low-Density Polyethylene Film

Table 7.7: Summary of the baseline process modelled for resin transfer molding [44]

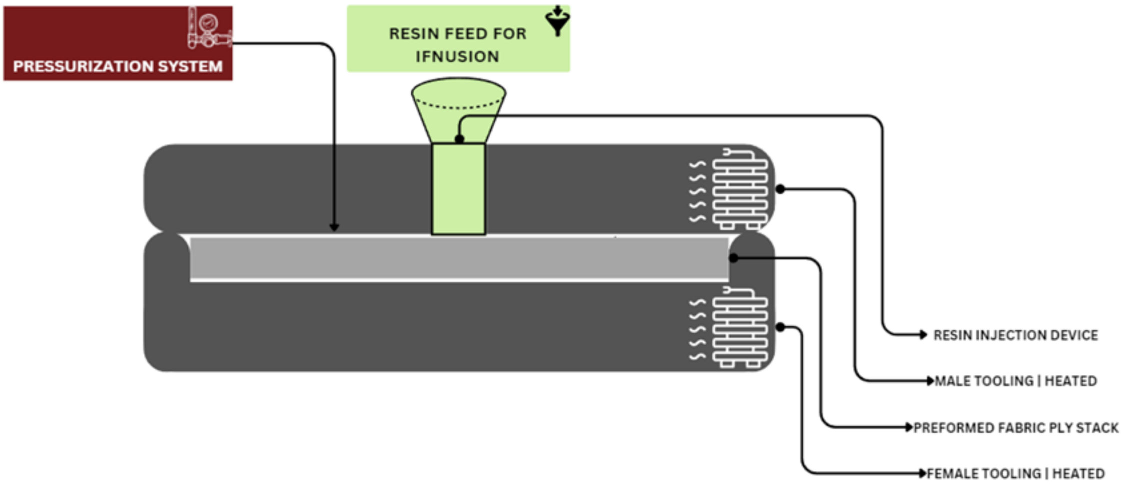

Figure 7.8: Simplified illustration of a resin transfer molding cycle

The waste percentages for fabric nesting, preform and product trimming were based on inputs from process experts, the production of auxiliary materials was modelled based on specific grades, their amounts calculated from areal estimations of the product, and the energy demand was based on measurements under simulated production environment conditions at the aforementioned Netherlands site.

7.5.4. Press Consolidation

Press consolidation is the out-of-autoclave processing variant for thermoplastic composites. Essentially modelling for high-volume production for thermoplastic composite components based on the current state of technologies, the preparation of the laminate used an input for press consolidation materializes in methodical steps. At first, cut off within the scope of this study due to insignificant impact, the process of slitting snips the prepreg roll into tapes of a required width for the successive step. The next step is that of automated tape laying. Here, a multiple degree of freedom robot lays, ultrasonically tacks, and cuts the tapes to generate a ply stack possessing gross product geometry with design layer-wise fiber orientations. In consultation with process experts at GKN Aerospace©, negligible quantities of waste were modelled to be generated under optimized series production conditions. This stack is then heated to mobilize the matrix enough and compacted over a cold mould to obtain an unconsolidated preform with gross product topology. This preform is then heated and compacted in a mould under controlled conditions for a stipulated period based on the process-specific recipe to finally obtain a consolidated product. Figure

7.9 shows a simplified version of the said system. The consolidated laminate is then trimmed to obtain the final, net product shape. One of the benefits of this sequence was deemed to be faster processing and the no auxiliary materials being required in contrast to the autoclave consolidation.

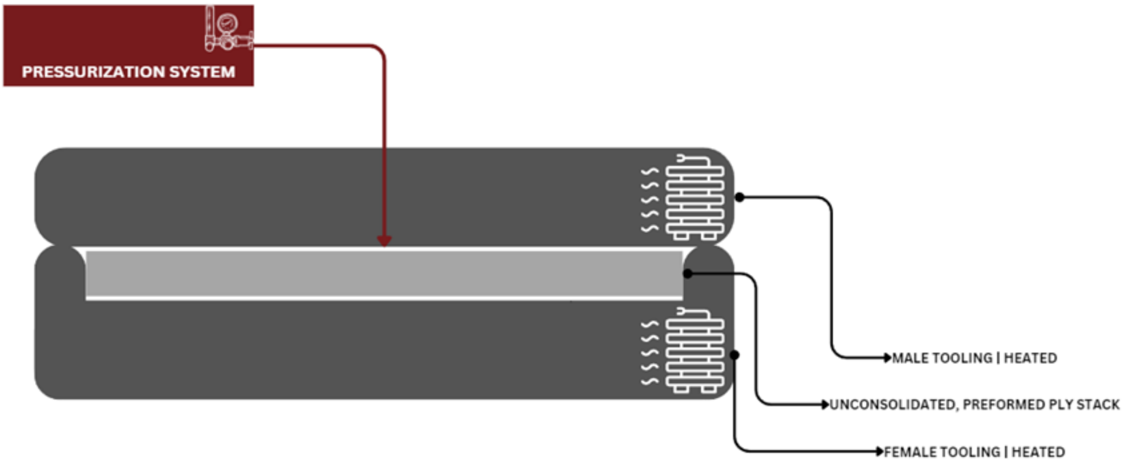

Figure 7.9: Simplified illustration of a press consolidation cycle

PRODUCTS MANUFACTURED PER CHARGE	1
CONSOLIDATION CYCLE PARAMETERS	
Dwell Temperature (°C)	375
Dwell Duration (minutes)	20
AUXILIARY MATERIALS	
Cleaning Agent	Isopropanol
Release Agent	Solvent-Based Release Agent

Table 7.8: Summary of the baseline process modelled for press consolidation [43]

7.6. Data Quality Assessment Scores

Each of the systems contained data aggregated from a variety of sources, a combination of measurements, calculations, and estimations. For the perfect system model, the overall score would be 1, a perfect representation of reality. But the gaps in data necessitated the system models to include a combination of measured, calculated, estimated data from a variety of sources. Still, the overall data quality scores for each of the systems was calculated to be $\approx$2. The spider charts in Figure **??** illustrate the average scores per scenario per quality indicator. Average scores for reliability and geograaphical representativeness were observed to be highest but within acceptable limits, $\approx$3, attributed primarily to low geographical resolution for the data related to material production sourced from life cycle inventory databases. The electricity grid mixes also contributed to this increase in score, reported as national averages. On the other hand, the scores for completeness and technological representativeness being close to perfect across systems instil high confidence in the impacts to be computed with this data as input.

Figure 7.10: Spider charts illustrating average data quality scores per indicator for the aggregated inventories of the respective system scenarios

8

Life Cycle Impact Assessment

As stated in the scope definition [Section 6], the impact assessment methodology employed is the one recommended as part of the Product Environmental Footprint Guidelines from the European Commission. As for the indicators, the evaluation shall account for the following [36].

- **Acidification:** Emissions, absorbed across the lithosphere, the atmosphere, and the hydrosphere, have been attributed to a series of chemical reactions responsible for reducing the overall pH of the affected soil, air, and water bodies. Contributing substances are scaled and expressed as mole equivalents of hydron, the cationic form of elemental hydrogen.
- **Climate Change:** It is responsible for representing the increase in average global temperatures because of greenhouse gas emissions. The general unit of expression is kilogram of carbon dioxide equivalent, all the greenhouse gases' warming potentials scaled to the impact of one kilogram of carbon dioxide.
- **Ecotoxicity (Freshwater):** Certain biological, chemical or physical stressors are known to affect the functioning of an ecosystem, some substances possessing tendencies to accumulate in certain organisms. In the scope of freshwater ecosystems, contributing substances are characterized and expressed in Comparative Toxic Unit for Ecosystems (CTUe).
- **Eutrophication:** This represents the ramifications due to substances containing nitrogen and phosphorus. On the terrestrial front, these nutrients encourage the growth of algae and other specific plants limiting the growth of the original ecosystem. Contributing substances are scaled and expressed as mole equivalents of nitrogen. As for freshwater, the algae growth depletes waterbodies of their oxygen content, drastically affecting the existing ecosystem. Contributing substances are scaled and expressed as mole equivalents of phosphorus. A similar impact as that for freshwater has been observed on marine bodies as well, the contributing substances scaled and expressed as kilogram equivalents of nitrogen.
- **Human Toxicity:** This represents the potential impacts on human health by absorbing substances, carcinogenic or otherwise, through the air, soil, or water. The repercussions are expressed as Comparative Toxic Unit for Humans (CTUh).
- **Ionising Radiation:** Under normal operating conditions, the prospective repercussions on human health are computed as kilobequerel equivalents of Uranium 235.
- **Land Use:** Transformation of the available land for agriculture, mining, construction or other purposes affects, among other things, the organic content of the soil, erosion levels, and species existing in the area. The induced impact measures the altered soil properties (biotic production, erosion resistance, mechanical filtration, and groundwater regeneration) in points.
- **Ozone Depletion:** The role of the stratospheric ozone layer in protecting life on earth from hazardous ultraviolet radiation is common knowledge. Its depletion has been attributed to increased risk of skin cancer in humans and functional damage to the plant kingdom. The impact of contributing substances is scaled and expressed as kilogram equivalents of chlorofluorocarbons-11.
- **Particulate Matter:** It is responsible for representing the adverse effects on human health due to particulate matter as well as precursor (NOx, SO2) emissions. The potential impact is expressed in disease incidence per kilogram of PM2.5 emitted.

- **Photochemical Ozone Formation:** At the ground level, increased ozone concentration affects organic compound constituents in plant and animal systems while also contributing heavily to the formation of photochemical smog. Contributing substances are scaled and expressed as kilogram equivalents of non-methane volatile organic compounds.
- **Resource Use:** This essentially is an umbrella term for representing the exploitative use and extraction of high-concentration, non-renewable resources. Fossil depletion is expressed in megajoules, while that of minerals and metals are characterized and converted into kilogram equivalents of antimony.
- **Water Use:** This is meant to quantify the depletion of available water from the region of influence for the activity under scrutiny, expressed in cubic metres of water use.

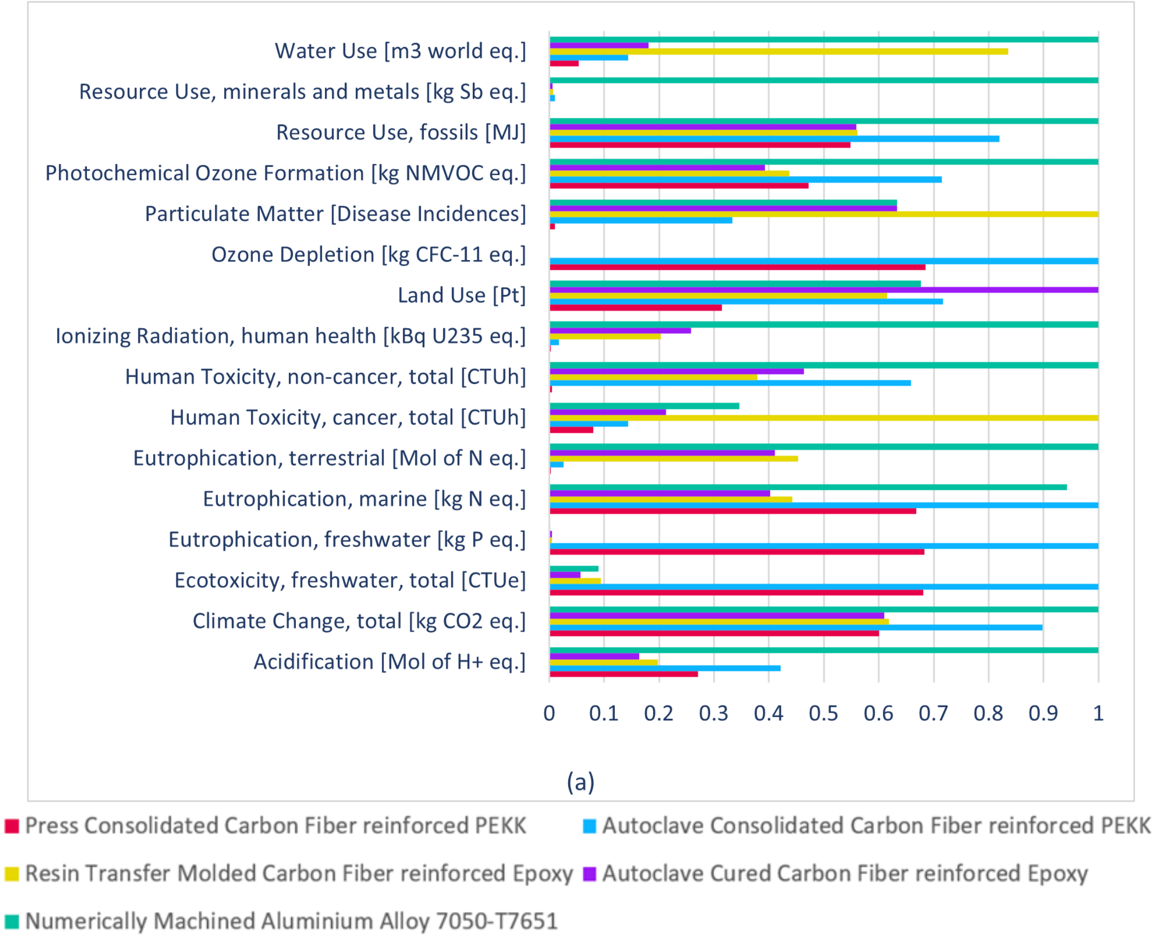

Figure 8.1: Characterization results for life cycle impact assessment characterized using the Environmental Footprint 3.0 methodology for cradle-to-gate Phases [Normalized to Maximum Impact per Category]

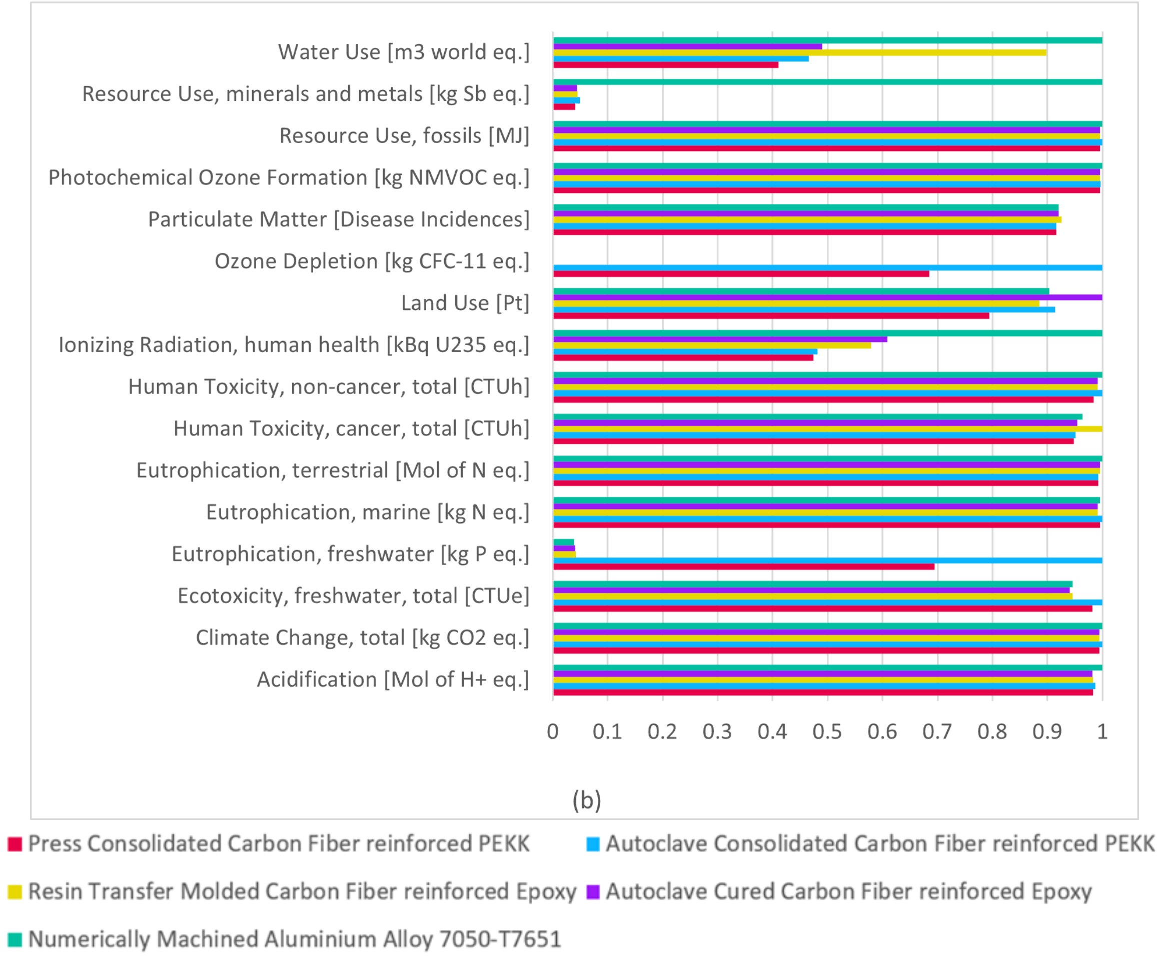

Figure 8.2: Characterization results for life cycle impact assessment characterized using the Environmental Footprint 3.0 methodology for cradle-to-end of service Phases [Normalized to Maximum Impact per Category]

The characterization results are illustrated in Figure 8.1 and Figure 8.2. For the cradle-to-gate phases, the aluminium alloy alternative being the least preferred option for most impact categories. The results for composite variants are more diverse across the board, difficult to select the "best" variant under undefined weighting conditions to rank impact categories against one another. Under the pretext of equal weight being imparted to each impact category, autoclave consolidated carbon fiber reinforced PEKK performs the worst of the composite variants, followed by resin transfer molded carbon fiber reinforced epoxy, autoclave cured carbon fiber reinforced epoxy, and press consolidated carbon fiber reinforced PEKK in increasing order of preference. Extending to include the operational phase, the results are significantly influenced by the kerosene production and combustion over the service life and seem to homogenize across most impact categories.

9
Life Cycle Interpretation

Section 8 lays the foundational knowledge base with regards to the scenarios under scrutiny. The baseline impact results reflect the state of the systems only under the assumptions made for the features and properties of the product systems, changes to which are expected to influence the respective impacts. Contribution analyses were conducted to give some insight into the magnitude of influence of each life cycle stage to the overall ecological profile, followed by sensitivity analyses explicitly addressing changes in product weights and the fly-to-buy fractions, to contextualize the aforementioned interdependence.

9.1. Contribution Analyses

One of the major benefits for out-of-autoclave composite manufacturing processing, other than faster processing times, is the minimal requirement of fewer auxiliary materials, which might be attributed to some magnitude of environmental efficiency. To this end, auxiliary material manufacturing per demand was quantified as a separate fraction the product manufacturing, and its contribution treated as an isolated stage in the life cycle.

The lack of transparency in the environmental profile of the material production for carbon fiber reinforced polyetherketoneketone plays in evidently in the contribution analysis [Figure 9.1]. The supplied profile missed characterizations for ionizing radiation, human toxicity, and terrestrial eutrophication. If this was due to negligible impacts for these categories or just a methodological choice was not explicitly stated and hence forms a limitation in context of this study. An especially large spike was seen at the ozone depletion potential for thermoplastic composite scenarios, attributed predominantly to matrix (polyetherketoneketone) production. Auxiliary material production appears to contribute heavily in the scenario concerning autoclave curing for a couple of the categories, a large spike is observed at the ozone depletion category, attributed predominantly to the production of polyvinyl fluoride, the material grade for peel ply and separation film used. Auxiliary material production effects on objective impacts when moving towards out-of-autoclave prospects was also observed to diminish significantly, conforming with expectations. An outlier was the case for ”Human Toxicity, cancer, total” for the Resin Transfer Molding Scenario. This was largely attributed to polyethylene production (covering film at fabric preforming), an auxiliary material unique to this scenario in context of the present study. As for the cradle-to-end of service analyses, the operational phase, i.e. kerosene production and combustion dominate heavily across impact categories and scenarios [Figure 9.2], the impact being as high as 99% for some scenarios and categories.

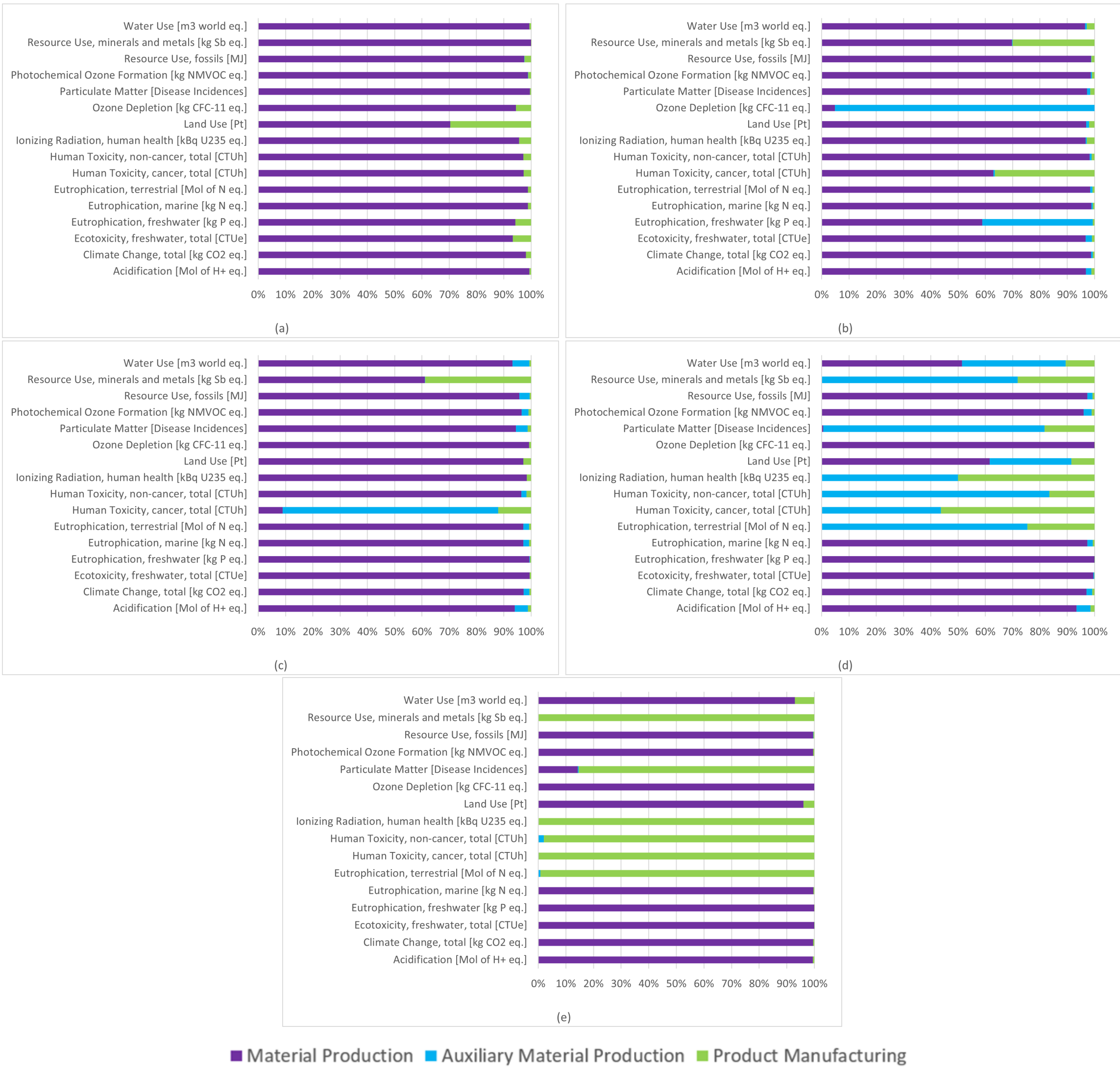

Figure 9.1: Contribution analyses for baseline scenarios over the cradle-to-gate phases (a) Numerically machined aluminium alloy 7050-T7651 (b) Autoclave cured carbon fiber reinforced epoxy (c) Resin transfer molded carbon fiber reinforced epoxy (d) Autoclave consolidated carbon fiber reinforced polyetherketoneketone (e) Press consolidated carbon fiber reinforced polyetherketoneketone

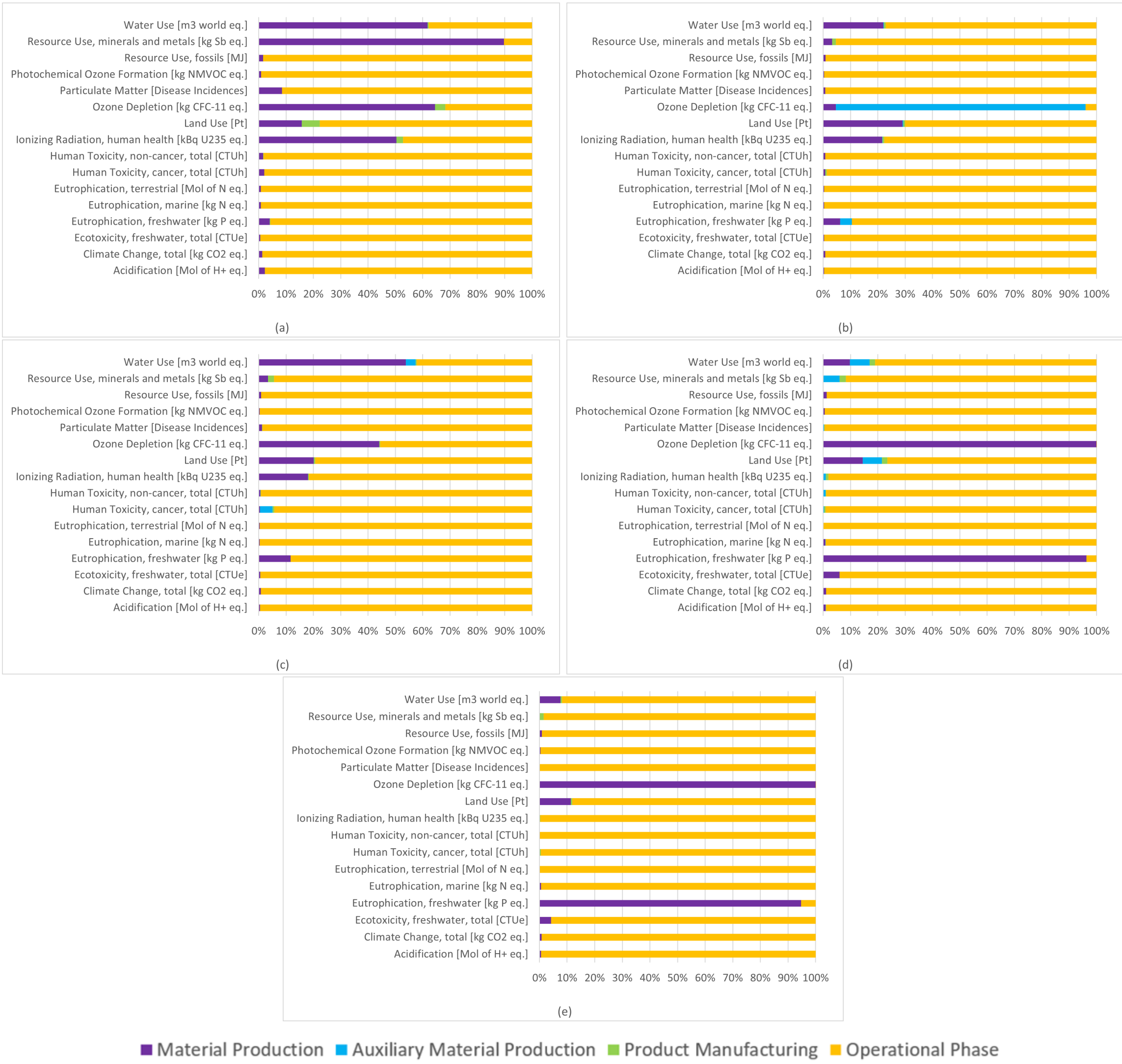

Figure 9.2: Contribution analyses for baseline scenarios over the cradle-to-end of service phases (a) Numerically machined aluminium alloy 7050-T7651 (b) Autoclave cured carbon fiber reinforced epoxy (c) Resin transfer molded carbon fiber reinforced epoxy (d) Autoclave consolidated carbon fiber reinforced polyetherketoneketone (e) Press consolidated carbon fiber reinforced polyetherketoneketone

9.2. Environmental Impact Sensitivity to Product Mass - Objective Modelling

The baseline computations work under the assumption that the products weigh 2.1 kg at the gate for all the material/manufacturing systems. Keeping the fly-to-buy fractions and the mass of the aircraft system constant, the mass of the product was changed to 1.5kg, 2.5kg, and 3kg, the change assumed to be balanced such that take-off mass was unchanged. It was observed that the quantitative environmental profile saw a linear increase/decrease across indicator categories with the same factor by which the product mass changes. Focusing on specific life cycle phases, the outcome seems reasonable for the operational phase since the assumption of a drop-in product implies a linear increase in mass-induced specific emissions over the service life. Over the cradle-to-gate phases, further insight might be needed to verify how representative the linear trends would be. As is, the systems were modelled to scale linearly in resource demand and emission profile per a similar setup for a larger or smaller product. For instance, certain auxiliary materials or processes might be dependent on other factors such as product series/production volume and might need to be accounted for with number of products as the reference flow, or a higher or lower product mass might be calling for a different topology, hence a different equipment

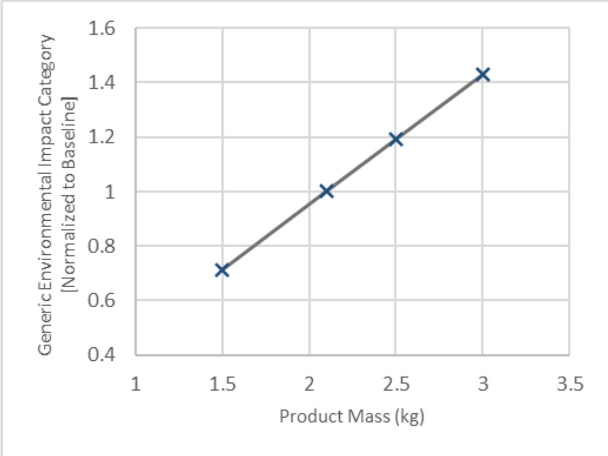

Figure 9.3: Environmental impact sensitivity to product mass - Objective - Generic Environmental Impact Category [Normalized to Baseline]

and manufacturing setup. The datacards on the software environment at the time of conduction of this study were programmed to have mass as the reference flow for the baseline scenarios across the board, the unit with the lowest deemed uncertainty linked to it. Hence, the computed impacts were observed to scale linearly.

9.3. Environmental Impact Sensitivity to Product Mass - Prospective Modelling

Another perspective of evaluating the sensitivity of the environmental profile to the product weight is to evaluate for the effects of lightweighting for one material grade over another. As highlighted in Section 7.2, each of the systems has been modelled to produce drop-in products possessing the same mass as baseline. But it is widely acknowledged, owed to a higher strength-to-weight ratio, composite structures carry lightweighting potential, upto . This, when combined with the mass-based fuel demand and combustion over the operational phase, as also highlighted in the findings of Arblaster [19], A.J. Timmis et al [22], and L. Scelsi et al [21], can alter the environmental profile greatly. To this end, three analyses were set up for assessing this lightweighting potential, setting the mass of the metal alloy product to be higher by about 30% over the baseline per an approximation of the differences in density between the metal and the composite systems, and alternating for the composite products between the baseline and an assumed state of a 15% heavier product to represent the uncertainty due to a design change as per the rest of the structure, and computing results normalized to the maximum impact. Note that this sensitivity analysis was meant to purely to illustrate a trend of dependence of the environmental impact on product mass possessing significant levels of uncertainty. The variations might not be representative of objective changes in mass if material systems were swapped for a given product.

Over the cradle-to-end of service phases, the results were straightforward due to the operational phase being extremely influential, the lighter variant being preferred always with the difference in impacts of the manufacturing methods having negligible influence on the outcome. Over the cradle-to-gate phases, the heavier aluminium product was never the preferred option. For the case of different masses associated with the two composite material system-based products, the outcomes were not as simple as the lightest one being chosen. Here again, the weighting set for the impact categories would need to be defined to definitively justify the choice of one over the other. Under the assumption of equal weight being imparted to all impact categories, press consolidated carbon fiber PEKK product was the preferred option unless the carbon fiber reinforced epoxy product is lighter, in which case, the autoclave cured carbon fiber reinforced epoxy product had the lowest impact score.

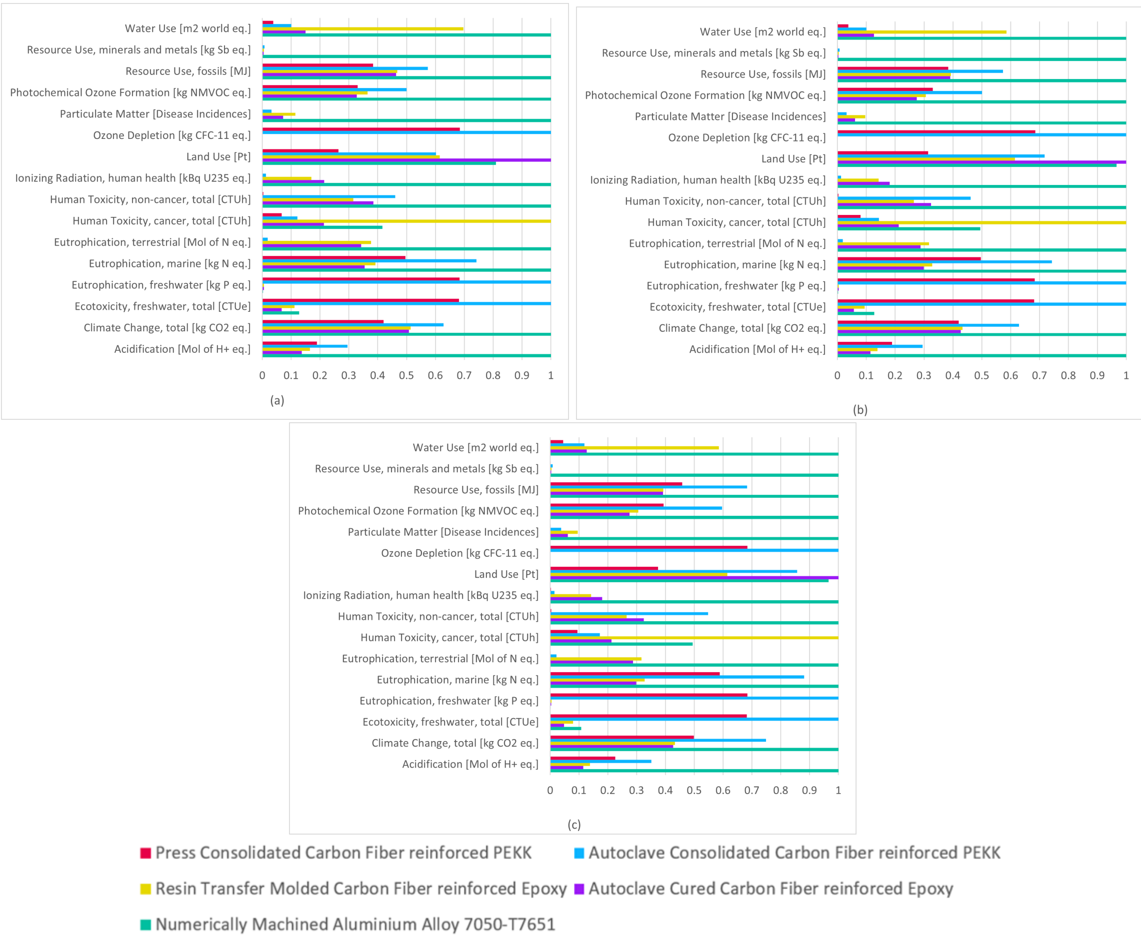

Figure 9.4: Cradle-to-gate impact sensitivity to product mass for (a) Aluminium alloy rib = 3kg, carbon fiber reinforced epoxy rib = 2.5kg, and carbon fiber reiforced rib-2.1kg, (b) Aluminium alloy rib = 3kg, carbon fiber reinforced epoxy rib = 2.1kg, and carbon fiber reiforced rib-2.1kg, and (c) Aluminium alloy rib = 3kg, carbon fiber reinforced epoxy rib = 2.1kg, and carbon fiber reiforced rib-2.5kg

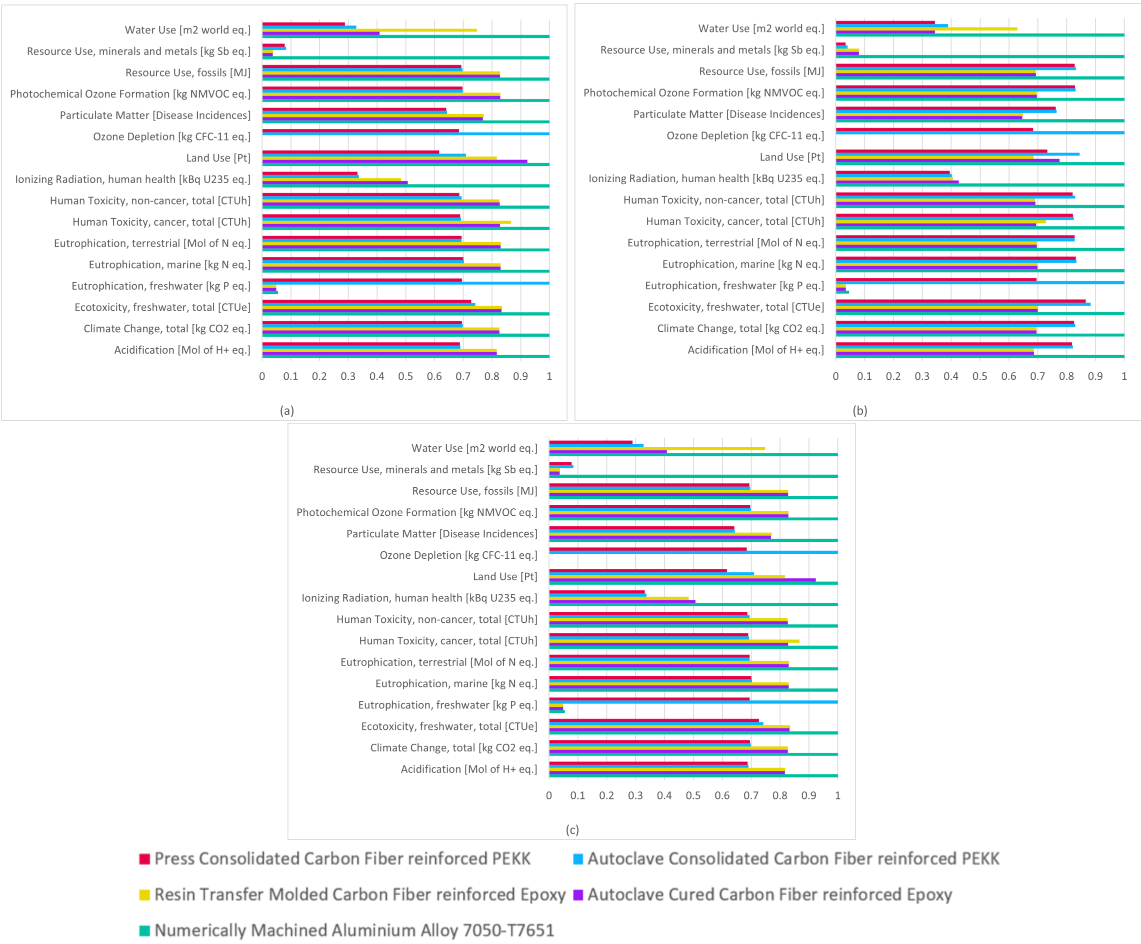

Figure 9.5: Cradle-to-end of service impact sensitivity to product masses for (a) Aluminium alloy rib = 3kg, carbon fiber reinforced epoxy rib = 2.5kg, and carbon fiber reiforced rib-2.1kg, (b) Aluminium alloy rib = 3kg, carbon fiber reinforced epoxy rib = 2.1kg, and carbon fiber reiforced rib-2.1kg, and (c) Aluminium alloy rib = 3kg, carbon fiber reinforced epoxy rib = 2.1kg, and carbon fiber reiforced rib-2.5kg

9.4. Sensitivity Analysis – Fly-to-Buy Fraction

Reiterating, the computations for the baseline scenarios were conducted at specific waste quantities, and hence, fly-to-buy fractions. These may be subject to further optimization or worsening depending upon the resources and time invested at the process design stages, and the inherent maturity of the processes.

9.4.1. Numerical Machining - Aluminum 7050-T7651

For the numerical machining of a component, the volumetric size of the initial billet is largely dependent upon the geometry of the final product. For more intricate topologies, a relatively larger billet might be required, while for simpler, more straightforward milling operations, a smaller billet and hence a better fly-to-buy fraction may be expected. Since the product design carries large uncertainties, the sensitivity analysis took a ±5% on the baseline fly-to-buy fraction, reflected largely in the increased/decreased raw material requirement. It is important to highlight that where relevant, the energy and resource demand were scaled linearly from the baseline scenario.

9.4.2. Autoclave Cured Carbon Fiber reinforced Epoxy

Much of the waste for this scenario was modelled, backed by industry knowledge, to be generated at the prepreg ply cutting and nesting stage. For projects with larger product series, this number could be brought down a significant amount, or could go the other way where a less optimized system produces even greater quantities of waste. Here as well, the sensitivity analysis took a ±5% on the baseline fly-to-buy fraction, reflected in the increased/decreased raw material requirement keeping the gross product (preceding the final milling to obtain final product) unchanged from the baseline, and the energy and resource demand, where relevant, scaled linearly from the baseline scenario.

9.4.3. Resin Transfer Molded Carbon Fiber reinforced Epoxy

Like the autoclave cured product, a large proportion of the waste generated was attributed to the fabric ply nesting stage. Yet again, projects with larger product series, this waste fraction could be improved significantly, or for the case of a less optimized system, produce an even greater quantity of waste. The sensitivity analysis took a ±5% on the baseline fly-to-buy fraction, reflected in the increased/decreased raw material requirement keeping the gross product (preceding the final milling to obtain final product) unchanged from the baseline, and the energy and resource demand, where relevant, scaled linearly from the baseline scenario.

9.4.4. Autoclave Consolidated Carbon Fiber reinforced PEKK

The process flow, at least the steps, for autoclave processes modelled in the scope of this study are similar to a great extent, also resulting in the same fly-to-buy fraction for both scenarios. The primary differences are in the details of the processes, the difference in processing conditions calling for different auxiliary materials and energy demands. Hence, the prepreg ply cutting and nesting stage was linked to the majority contributor to waste production and subject for optimization. Yet again, projects with larger product series, this number could be brought down a significant amount, or could be a less optimized system with higher waste generation The sensitivity analysis took a ±5% on the baseline fly-to-buy fraction, reflected in the increased/decrease raw material requirement keeping the gross product (preceding the final milling to obtain final product) as is from the baseline, and the energy and resource demand, where relevant, scaled linearly from the baseline scenario.

9.4.5. Press Consolidated Carbon Fiber reinforced Polyetherketoneketone (PEKK)

As opposed to the other composite material-based scenarios, here the sensitivity analysis, although still reflected in increased/decreased raw material demand, the change is modelled to occur at the gross product stage. A more or less optimal gross product would result not just in an altered raw material demand, but also the energy and auxiliary material demands due to a smaller or larger substrate, respectively. The sensitivity analysis took a ±5% on the baseline fly-to-buy fraction, the energy and resource demand being scaled linearly from the baseline scenario where required.

9.4.6. Results

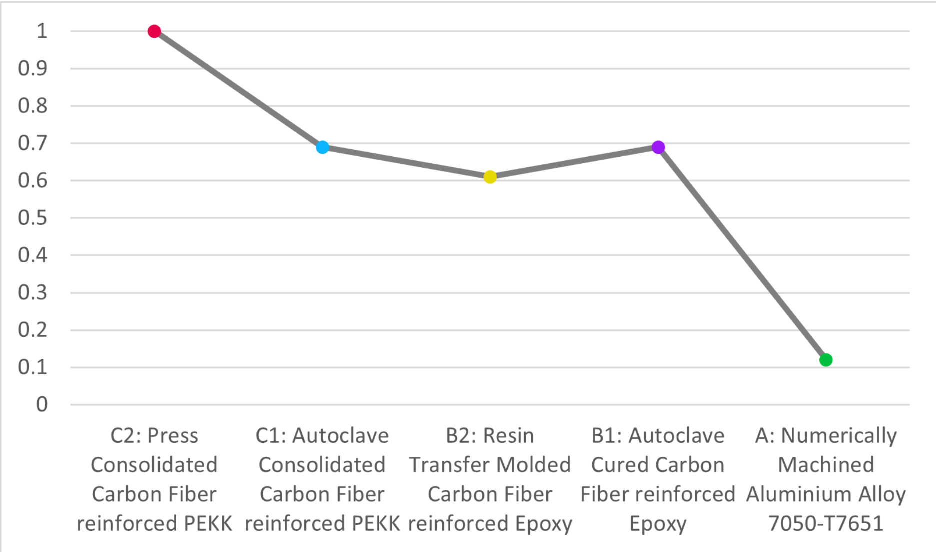

Figure 9.6: Baseline fly-to-buy fractions per scenario normalized to that for scenario C2; press consolidated carbon fiber reinforced PEKK

Figure 9.7 illustrates the results of the sensitivity of the environmental impact on the fly-to-buy fraction, normalized to the baseline per scenario. The results, illustrated in the form where they have been normalized to the baseline per scenario, were found to be valid across impact categories. Since the baseline scenario possesses a relatively lower fly-to-buy fraction, the aluminium alloy product was observed to be highly sensitive, increasing by almost three times for the higher fly-to-buy fraction. With the lowest fly-to-buy fraction at the baseline, the press consolidated product was not observed to be as responsive to changes in the fly-to-buy percentages, fluctuations being well within 10% at either end.

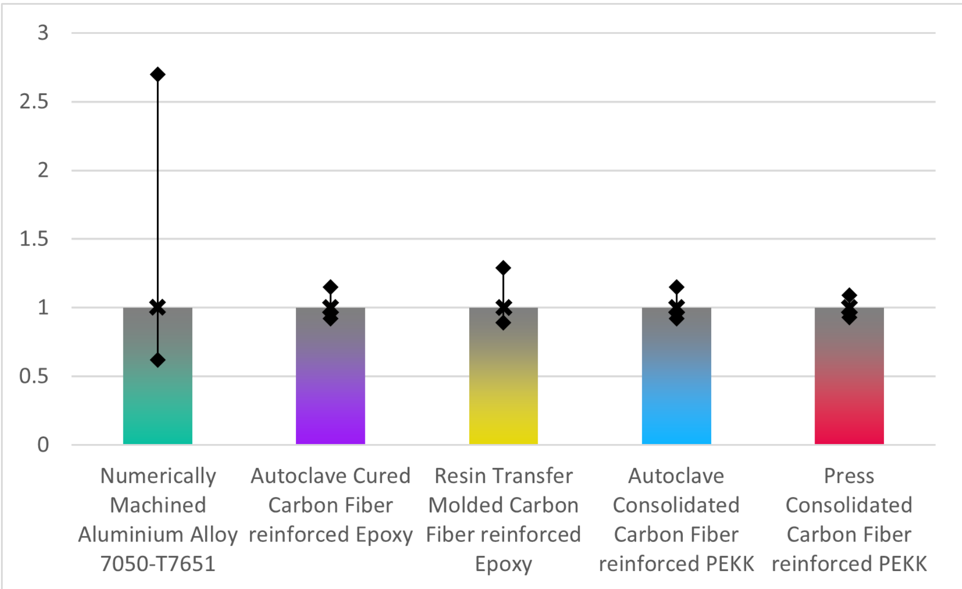

Figure 9.7: Environmental impact sensitivity to fly-to-buy fraction per scenario [normalized to baseline]

10

Burden/Benefit Allocation - Case Study of a Secondary Aircraft Structure

Burden and benefit allocation has been projected in negative light across guidelines and methodological frameworks, discouraging the practice as and when possible. But with increased interest in circularity and progression towards leaner manufacturing units, practices of reuse at end-of-life where possible, and recycling/downcycling of waste streams requiring the same are being encouraged, This seems counterintuitive and was hence taken up in the scope of this project. GKN Aerospace© partnered with industry-leaders including but not limited to Thermoplastic Application Centre©, Thermoplastic Research Centre©, Toray Advanced Composities©, and Dutch Thermoplastic Composites© (now Collins Aerospace©) to demonstrate a consolidated waste processing technique delineated in Figure 10.1. Consolidated carbon fiber reinforced thermoplastic waste, once collected, is shredded, blended with polymer pellets via heated, low-shear mixing, and then compression molded into the geometry of a product. The manufactured recycled product was tested for mechanical strength by de Bruijn et al [29], and found to be more than suitable to replace secondary structures, manufactured via virgin metal alloys and/or virgin carbon fiber reinforced epoxy in current state, not only satisfying the mechanical requirements, but also producing a lighter product with the prospect of further environmental benefits downstream.

10.1. Case Study - Arbitrary Secondary Structure

The aforestated process was modelled to be included in the system boundaries of the press consolidated carbon fiber reinforced polyetherketoneketone product system (Scenario C2), consolidated waste generated at product trimming was modelled to be reprocessed and converted to 1 kg of secondary, recycled material in a state wherein it can be substituted as a virgin raw material for compression molding into an arbitrary product topology. Polyetherketoneketone pellets were modelled for as the polymer added at the low-shear mixing stage. Three prospective scenarios were set up to compare the environmental profile per indicator wherein the recycled carbon fiber reinforced polyetherketoneketone substrate was to replace a product to

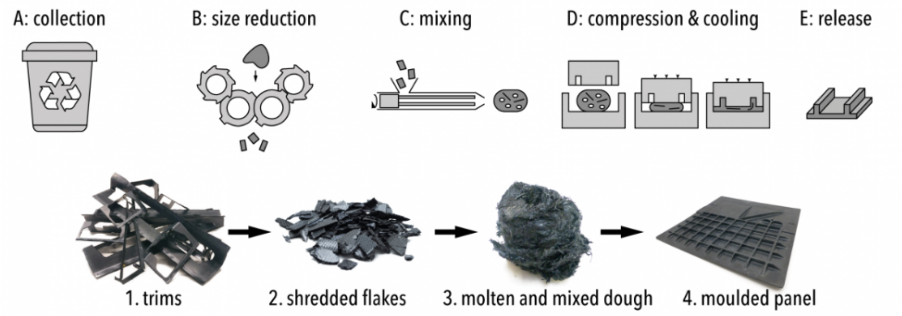

Figure 10.1: Recycling process flow for processing consolidated carbon fiber reinforced thermoplastic waste (a) Shredding (A to B) (b) Heated, Low Shear Mixing (B to C) (c) Direct Compression Molding (C to D) [29]

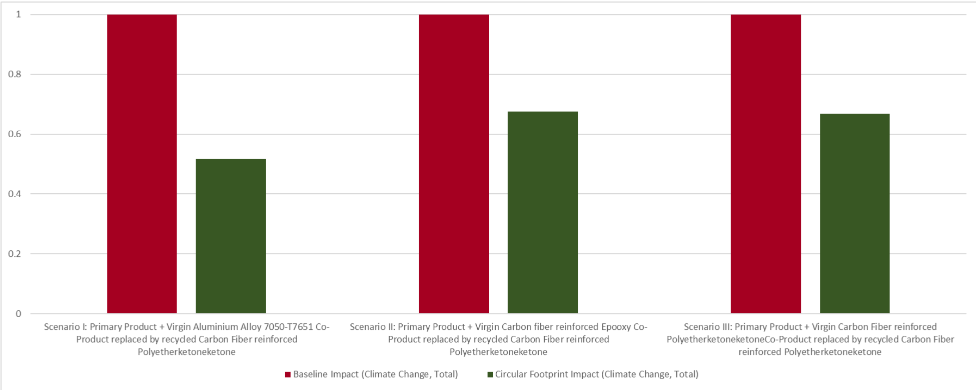

Figure 10.2: ”Climate Change, Total” impacts normalized to the baseline for quantifying the benefit of substituting recycled carbon fiber reinforced PEKK for virgin (a) Aluminium Alloy 7050-T7651, (b) Carbon fiber reinforced Epoxy, and (c) Carbon fiber reinforced PEKK in a secondary aircraft structural component

be manufactured via virgin aluminium alloy 7050-T7651, virgin carbon fiber reinforced epoxy, and virgin carbon fiber reinforced polyetherketoneketone.

The inventory for the energy demands for the various steps were based on primary data measured on-site at the facilities of Thermoplastic Application Centre© and GKN Aerospace©. R_1 was set to zero, the material at input in the primary product system modelled to be fully virgin. The quality fraction at output was modelled to be 1, since the mechanical demands for the product were assumed to be met fully, per the findings of de Bruijn et al. Since the supply chain for recycled carbon fiber reinforced thermoplastic composite material can be described as nascent at best, the allocation factor was set to 0.5, depicting an economic balance of supply and demand, the burdens and benefits being apportioned equally between the primary and the co-product system.

The baseline system for each scenario was modelled as the primary product being manufactured as is with no waste stream processing and the material production accounted for per the demand of the co-product system possessing a reference mass of 1 kg. It is important to highlight that the baseline fly-to-buy fractions, as used in Chapter 7, were applied to compute the raw material demand per scenario. The circular footprint approach was modelled to substitute for the respective raw material demands with the recycled carbon fiber reinforced polyetherketoneketone material in combination with the primary system. The results, depicted in Figure 10.2, were computed for the category ”Climate Change, Total” and the results normalized to the baseline system. A significantly improved environmental performance was observed across the board, $\approx$49% decrease in objective impact when replacing virgin aluminium alloy, and $\approx$33% when replacing carbon fiber reinforced polymer variants. Due to limited availability of data for other impacts for PEKK pellets, the analysis was limited to kilograms of carbon dioxide equivalents, solving the purpose of illustrating the implementation of the circular footprint approach in the scope of allocation in primary to co-product systems, while maintaining a high-confidence dataset.

Part III

Insights, Recommendations, and Concluding Remarks

11
Discussion of Results

Having characterized the baseline environmental profiles for each of the scenarios, quantified the contribution of the various life cycle phases per system, and established a foundation for the sensitivity of the impacts on the features of the respective product system such as the final component mass and the fly-to-buy fraction, this section intends to contextualize these findings from the perspective of the state-of-the-art. Objectively, the data quality assessment described the extent of representativeness of the systems modelled with regards to reality or the expected state, the overall scores for each of the system scenarios being 2, lying predominantly in the "Very Good" grade. From the comparative perspective, the quality scores across quality indicators for the systems overlap almost perfectly. This implies that not only are the aggregated inventories highly representative per scenario, the comparisons of impact profiles of each to the other is more like-for-like, the inventories being based on similar resource and time investments. This only adds to the confidence and credibility of the results within the bounds of the defined systems. Although it still comes as a recommendation in the international LCA frameworks, data quality assessment provided invaluable insight into the aggregated inventories throughout the conduction of the study not only with depicting the final quality, but also to better allocate time and resources to the aggregation of inventories of different systems to maintain the overlap.

An important addition to the state-of-the-art was the use of representative data to aggregate the inventory for carbon fiber reinforced PEKK prepreg supplied by material supplier. This was found to be a major gap in data availability across literature articles and life cycle inventory databases. Also, to the best of the author's knowledge, this study, at the time of publication, is the first to model for autoclave consolidation of carbon fiber reinforced PEKK based on primary process data for environmental profile construction. Although objective results have not been divulged in existing scope, the contribution analysis conducted provides insight into how these compare to the other life cycle phases. As for results of the characterization, on inclusion of the service life of the aircraft, the production and combustion of kerosene dominated the environmental impact across categories, up to 99% for "Climate change, total", homogenizing the scenario-specific impacts under the pretext of equal product weights. Since the emissions over the operational phase are predominantly mass-induced, a lighter product would almost always be the preferred variant regardless of the material and manufacturing route employed, further substantiated by the conducted sensitivity analyses. This is also well in line with findings of the literature survey, Arblaster [19] going on to quantify the weight difference between variants to by 3% for the lighter variant to take precedence over the others. The comparisons though are not as simplistic as this over the cradle-to-gate phases. Firstly, when modelled for the same product mass, more information regarding the weighting set being used to evaluate the final environmental profile would be needed. In other words, different applications, industries, or organizations may prioritize some impact categories over others, and by different factors at that. Hence, in the absence of insight into the difference in level of interest per impact category (if any), the environmental profiles have been commented on under equal weighting conditions, i.e., equal importance being imparted to all impact categories. Hence, at the baseline product mass over the cradle-to-gate phases, press consolidated carbon fiber reinforced PEKK product has the lowest impact, followed closely by autoclave cured carbon fiber reinforced epoxy. The large impact associated with the autoclave consolidated carbon fiber reinforced PEKK product, placing it as the fourth preference of five scenarios, was attributed to a high raw material demand owed to lower fly-to-buy percentage. As can be observed from the contribution analyses, material production phase is the most impact-intensive phase across impact categories for each of the composite material scenarios.

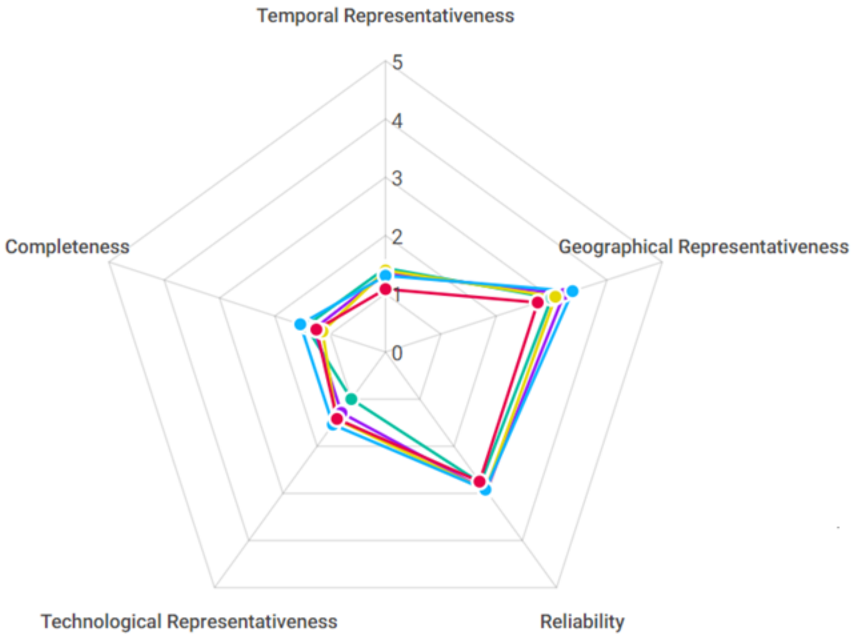

Figure 11.1: Superimposed spider charts for the data quality assessment scores per quality indicator for the scenarios under scrutiny

As highlighted in Section 2, studies by Stefanidi and Arblaster conducted life cycle analyses on a similar case study but under different system boundary definitions and impact characterisation methodologies in comparison to the scope of this discourse. The scope for Stefanidi's study was limited to quantifying the cumulative energy demand and the amount of carbon dioxide emitted over the course of the product life cycle while Arblaster constructed an environmental profile of the products according to the EF 3.0 methodology as well but excluding the category concerning "Water Use". Moreover, as opposed to this study having no secondary material inputs at the baseline systems, both these studies accounted for secondary (recycled) material inputs for the metal alloy scenarios, Stefanidi allocating the benefits and burdens directly at the point of substitution and Arblaster taking up the circular footprint technique with the manufacturing waste stream processing being included in the system boundaries. As for the operational phase, there were major differences not only in the features of the service lives modelled, but also in characterization results across the three studies under scrutiny, predominantly attributed to different sources being used to characterize impacts related to kerosene production and combustion. In addition to that, Arblaster and Stefanidi accounted for weight savings in their baseline computations already, placing the composite products to be $\approx$20% and $\approx$40% lighter than the composite counterparts, respectively. The final major methodological difference was the inclusion of the end-of-life treatment in the scope of studies by Stefanidi and Arblaster, excluded from this study simply because of the high uncertainty of the process that would be taken up. Since most aircraft with significant composite weight fractions are still in service, the quality of the waste that would be gathered at the end-of-life would be the driving factor to determine the route for further processing, i.e., reuse, recycling, downcycling, or incineration for thermal energy recovery for various proportions of the total waste streams. Acknowledging these differences and limitations, the results do still inform comparison of results for overlapping scenarios when including the operational phase.

Stefanidi's findings, only considering "Climate Change, Total" as the impact category of significance, illustrate a similar trend when comparing the environmental profiles across scenarios for the computations including the operational phase. Comparing the results over the contribution analyses over the cradle-to-end of service phases to those from Arblaster, the computed results tend to overlap well with those of Arblaster (differences within 10 ± 5%) for most impact categories across scenarios but not without some outliers. Firstly, for the press consolidated carbon fiber reinforced PEKK rib, categories of "Eutrophication, Freshwater” and “Land Use” were observed to have dissimilarity in the contribution of the material production phase to the overall life cycle, the former seeing more than 90% contribution to the overall impact while the latter seeing a contribution of about 10% over the material production phase in this study, while the results from Arblaster suggest about 25% of the impact for “Eutrophication, Freshwater” and negligible impact for “Land Use” being attributed to the material production phase. The other scenario having interesting outliers was that of the autoclave cured carbon fiber reinforced epoxy product. The results from Arblaster tend to underestimate the contribution of the prepreg production phase for the category of “Land Use” by 30%. Finally, the impact computed for “Ozone Depletion”, deemed to have almost no contribution from the material production/extraction phase per the findings of Arblaster had the largest mismatch across scenarios, the results of this analysis attributing as much as 99% of the impact to the said life cycle phase for the press consolidated carbon fiber reinforced PEKK and autoclave cured carbon fiber reinforced epoxy products. Hence, hotspot identification would produce different results, especially under the circumstance of the aforementioned impact categories inviting preference from practitioners during weighting.

As for a method of treating the consolidated waste stream for the case of thermoplastic composites, a separate case study was taken up. Again, this exclusion from the baseline systems was attributed to high uncertainty being linked to the methods of segregation and treatment of manufacturing waste that would be taken up under series production. The case study taken up assumed a product possessing a mass of 1 kilogram of an arbitrary geometry performing the function of a secondary, non-load bearing product over the life cycle of a given aircraft. The burdens and benefits shared between the primary wing rib production and the secondary component were allocated based on the circular footprint method, the results illustrating the environmental gain limited to the avoided virgin material production if the downcycled product were to replace a product manufactured via fully virgin aerospace-grade materials. Upto 50% reduction in the net impact was found to be achievable over an extended system boundary, associated with this avoided virgin material production. The isolation and communication of the results of allocation carried out via the circular footprint technique, as opposed to these being black-boxed within the baseline systems as was observed across existing publications, gives valuable insight into the positive environmental prospect of further development of composite recycling/downcycling techniques over production via virgin materials.

12
Limitations and Recommendations

12.1. Limitations

A series of assumptions and choices made by the practitioner through the course of this project, for a variety of reasons, had the biggest of roles to play in the obtaining the impact profiles as they were. This chapter shall address and scrutinize, to the best of the author's knowledge, the influence of these from a qualitative perspective.

12.1.1. Manufacturing Waste Streams – Further Treatment and Processing

In the baseline scenarios modelled, the treatment and further processing of the manufacturing waste was left out of the system boundaries. This was a conscious decision, being cognizant of the maturity and transparency of the treatment activities for the different materials carry great uncertainties. For instance, aluminum alloy waste carries great inherent potential of being recycled and fed back in as a substitute for raw material, accomplishing the goal of "circularity", in theory at least. This, in consultation with experts, was found to not be the current state. The recycling processes for metal alloys essentially deals with melting and purification of the substrate to obtain an alloy with desired composition and properties. This is only feasible in aerospace applications if the ingoing waste is perfectly traceable to a system, and the purity and composition of the final alloy can be ensured. Hence, in practice, the numbers around the recycling fraction, at least for primary load-bearing structure manufacturing, tend to run relatively low with high uncertainty. The Ansys Granta 2022 R1© states a 47.5% recycling fraction in the overall supply chain of Aluminium 7050-T7651. This gives rise to the practice of "downcycling", the processing of this waste into raw material for products with inferior quality demands, be it within the same system/application or elsewhere. On the other hand, composite component manufacturing was observed to produce multiple waste streams. For each of the systems, uncured/unconsolidated waste from the nesting stage, the auxiliary material waste after demolding the product, and cured/consolidated laminate waste from the final product milling could be the broad classifications. Per the norm, these have been modelled to be incinerated for thermal energy recovery. However, there have been multiple attempts to model the novel recycling/downcycling practices for materials from each of these waste streams within academia and the industry, the question again being the uncertainty tied to the maturity and existing state of these processes. If the waste streams were to be included in the system boundaries, the composite component manufacturing-related waste being modelled to be incinerated and the aluminum alloy waste being modelled to be recycled/downcycled at an arbitrary fraction, it was deemed to introduce a mismatch in treatment, while also inculcating uncertainty to an extent. It is also acknowledged that the inclusion and allocation, if performed with high quality data and suitable, relevant practices, respectively, will have a major influence on the impact profiles as modelled in existing scope. Also, the term downcycling, of course, here is subjective in its use. It might be the case that this waste could substitute the raw material in the existing system of an alternate product, seeing it exhibit superior properties compared to its original form from a different material, making a case for "upcycling" even.

12.1.2. Nondestructive Inspection and In-Service Maintenance

Another constituent in the production chain of component left out of system boundaries was the nondestructive inspection of products at the gate. This was purely due to the lack of high-quality data. Also, it was expected to not have a large influence on the overall impact while also being a practice of low interest for existing scope to invest time and resources for data collection. Although, some objective impact that was not modelled for must be acknowledged as a limitation, on the normalized scale, even for the cradle-to-gate scenarios, the influence is expected to be minimal. Extending it to in-service system, maintenance operations have been left out of the system for the same reasons of data unavailability and uncertainty. One interesting aspect to highlight is the prospective benefit of composite structures over conventional metal structures due to their resistance to corrosion and fatigue damage facilitating the possibility of longer service intervals between inspection. Within composite alternatives, thermoplastic composites also hold the prospect of convenient repair techniques over their thermoset counterparts which might have considerable influence on how the in-service behaviour is modelled [17]. Both these aspects, if and when modelled for, could significantly alter the specific impact, i.e., per passenger per km performance of the scenarios.

12.1.3. Influence of Component Material on Overall Structural Design

The material of the component has an influence not just on the design of the product itself, but also on the overall structure of the wing box, by virtue of the load distribution and material interface interactions due to difference in thermal expansion coefficients, among other things. Also, it is expected that composite structures exhibit a greater resistance to fatigue and micro-cracking eliminating the need for numerous inspection hatches over the wing skin [17]. Hence, the drop-in scenario modelled in this scope of this thesis is not the most representative but is a consequence of what can considered to be characteristic to comparative, hypothetical scenario-based environmental impact modelling. If the application were to demand the impact assessment of a more realistic system, it would require a much greater time and resource investment from upstream and downstream stakeholders, modelling the alternate scenarios in the space of their applications to be used as a feed for inventory aggregation and hence, into environmental profile construction. The sensitivity of impacts on the product mass would hence be a multivariate analysis and build a higher confidence dependence set.

12.2. Recommendations for Future Work

Characteristic to existing life cycle assessment studies, data availability could be termed as the lowest hanging fruit that would yield exponentially higher quality results than those reviewed in the state-of-the-art. An especially interesting flow worthy of primary data collection is the trapped volatile release not only from the substrate, but also from auxiliary materials during the manufacturing phase for autoclave processing. Another avenue for resource investment in data collection is that of waste stream processing. A large proportion of the existing commercial aircraft fleet is expected to end its service life in the coming decades. This could be treated as an opportunity for having some preparedness for technological developments for reprocessing the end-of-life waste. Prospective life cycle assessment studies could already prove useful in steering the development of both, the recycling/downcycling technologies and the respective framework for environmental modelling. Another area with large gaps is that of non-destructive inspection. Industry standard techniques for metal alloy products are known to employ certain solvents that might be attributed to some environmental impact, but has not been treated well in any of the existing studies.

Staying within the realm of inventory analysis, a critical element missing in the data quality assessment framework employed in this project was the ability to weigh the importance of certain flows and processes when qualifying the dataset for completeness. The completeness fraction does not, in any way, account for the contribution to impact that may be lost with the exclusion of certain flows or processes, treating each constituent of the system as a similar entity. This is one of the larger gaps that would need addressing to have a more robust system of data quality assessment. Another area of relevance for the development of weighting sets would be for results communication. As is, objective results can be hard for stakeholders, even practitioners, to get a grasp around. What may come off as jargon, could easily be reduced to a single score if a baseline impact profile supplemented by a weighting were to be constructed as part of a system of recommendations. The results from different studies, from within or across product systems and industries, would be much easier to compare and hence inform better decision-making.

13 Conclusion

Circling back to the research question this project set out to answer, as stated in Chapter 4, now that the suitable analyses have been conducted and the results computed, this section shall treat each of the sub-questions individually.

13.1. Sub-Research Question 1: Comparative Life Cycle Assessment over the Cradle-to-Gate Phases

As for the cradle-to-gate impact assessment results from Chapter 8, a majority of categories point away from the aluminium alloy alternative. This is predominantly attributed to poor buy-to-fly fraction associated with the system, demanding a larger volume of material to produce a product. It is difficult to identify and define the "best" performing alternative since the results produce indicate a mixed bag of preferences across impact categories. What can already be stated is that autoclave cured carbon fiber reinforced epoxy, resin transfer molded carbon fiber reinforced epoxy, and press consolidated carbon fiber reinforced polyetherketoneketone could be preferred across weighting sets applied to life cycle impact assessment categories, with autoclave consolidated carbon fiber reinforced polyetherketoneketone almost never being preferred. An interesting facet to highlight is that concerning the sensitivity of these results to product weight, under the same buy-to-fly fractions as from Chapter 9, a lower weight on the thermoset alternative would shift preference towards the autoclave cured carbon fiber reinforced epoxy product, while that on the thermoplastic alternative would see the press consolidated carbon fiber reinforced polyetherketoneketone being favoured, at least under equal weighting conditions for impact categories. The findings for the contribution analyses over the cradle-to-gate phases also conform with some trends observed per the literature survey [Section 2.2], the material production phase being dominant. The same could be attributed to extremely impact-intensive PAN-based production of carbon fiber, and that to poor buy-to-fly fractions for metal alloy scenarios, being much less impact-intensive to produce per unit mass, accumulate a worse profile.

13.2. Sub-Research Question 1: Comparative Life Cycle Assessment over the Cradle-to-End of Service Phases

Widely accepted and quantified across academic and industrial articles as the largest contributor of impact across most categories by heavy margins, the operational phase being included in the analysis required further substantiation by accounting for lightweighting prospects to be able to choose the right alternative. Per the findings described in Chapter 9, the lighter product is to be preferred, the aspect of product manufacturing process for a given material system losing significance across a majority of the categories, Here again, it must be reiterated that the impact assessment category weighting set applied to the computed impacts might end up narrating a different story but under the assumption of equal weighting, the lighter product with any of the respective production processes shall be preferred. Arblaster [19] quantified this weight difference for preferences to kick in to be about 3%. The findings align almost perfectly with those of the literature survey [Section 2.2] for this scope.

13.3. Sub-Research Question 3: Data Quality Assessment

Each of the datasets used as input to aggregate the life cycle inventories per scenario were assessed, scored and graded for under the system described in Section 5.4. Each of the overall scores being $\approx$2, while having a significant overlap in the radar charts when superimposed over one another, demonstrates not just representative objective datasets, but also the similarity in the quality of the datasets across data quality indicators adding an extra layer of credibility of the results, in purview the of methodological choices and assumptions. The recommended system for qualification and quality communication via spider charts is a robust framework for generating transparent, reproducible results.

13.4. Sub-Research Question 4: Prospects of Burden/Benefit Allocation via Circular Footprint Approach

A high quality, primary dataset was aggregated and used as input to compute the environmental impact of the recycling process, as described in Chapter 10. The practice of allocation implemented under the frame of assumptions was found to be robust and easy to implement. As the infrastructure around waste stream management activities matures, there should be greater insight available, not only with regards to the environmental data for reprocessing techniques, bu also for the values to be used for the fundamental variables for material classes specific to the aerospace industry, adding to the reproducibilty of the method.

13.5. Primary Research Question

Under an equally weighted set for prioritizing life cycle impact categories, under the assumptions and limitations of the modelled baseline systems in terms of fly-to-buy fractions and equal product masses, press consolidated carbon fiber reinforced PEKK would be the preferred option over the cradle-to-gate phases, followed closely by autoclave cured carbon fiber reinforced epoxy. Accounting for lightweighting prospects for composite variants over the metal alloy would only see an increase in the disparity of impacts. But, if one composite product is modelled to outweigh another, drawing conclusions becomes increasingly difficult because of the shear diversity across impact categories. When including for the service life, the lighter product would almost always be preferred, press consolidation being preferred over autoclave consolidation for thermoplastic variants, and autoclave curing being preferred over resin transfer molding for the thermoset variants.

Continuous technological development has always had, and will continue to cause some interference with the planetary boundaries. Qualitative statements and opinions have been the foundation for steering development in the last decades. The framework of life cycle assessment, also applied in the scope of this project, provides invaluable quantitative inputs on these matters, eliminating ambiguity for times when these are fed as inputs in decision-making downstream. This thesis intended to progress the understanding of aerospace material and manufacturing systems, comparing them against one another from an environmental perspective, adding industrially-representative results based on qualified data. The constructed environmental profiles shall form for more informed and aware solution-based approaches in the future.

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A

Scoresheets - Data Quality Assessment

Element Type	Name	Data Quality Indicator Score								
		Temporal Representativeness	Geographical Representativeness	Reliability	Technological Representativeness					Completeness
					Process Design	Operational Parameters	Material Grade Specificity	Process Scale	Score	
Aggregated Process	**Aluminium Ingot Production**	**3**	**3**	**3**	YES	YES	YES	YES	**1**	**1**
Aggregated Process	**Zinc Production**	**1**	**4**	**3**	YES	YES	YES	YES	**1**	**1**
Aggregated Process	**Copper Production**	**3**	**5**	**3**	YES	YES	YES	YES	**1**	**1**
Aggregated Process	**Magnesium Production**	**1**	**2**	**3**	YES	YES	YES	YES	**1**	**1**
Aggregated Process	**Electricity Production Mix [United Kingdom]**	**1**	**3**	**3**	YES	YES	YES	YES	**1**	**1**
Aggregated Process	**Aluminium Alloy 7050-T7651 Production**	**1**	**5**	**3**	YES	YES	YES	YES	**1**	**5**
Intermediate Flow	Aluminium	1	5	3						
Intermediate Flow	Zinc	1	5	3						
Intermediate Flow	Magnesium	1	5	3						
Intermediate Flow	Copper	1	5	3						
Energy Flow	Energy Demand | Alloying	1	5	3						
Intermediate Flow	Aluminum Alloy 7050-T7651 Billet	1	1	2						
Aggregated Process	**Diesel Production**	1	**3**	**3**	YES	YES	YES	YES	**1**	**1**
Aggregated Process	**Truck-trailer Transport**	**1**	**5**	**3**	YES	YES	YES	YES	**1**	**1**
Intermediate Flow	Diesel | Truck-trailer Consumption	1	5	3						
Intermediate Flow	Cargo | Aluminum Alloy 7050-T7651 Billet	1	5	2						
Aggregated Process	**Petroleum-based Lubricant Production**	**1**	**3**	**3**	YES	YES	YES	YES	**1**	**1**
Aggregated Process	**Numerical Machining Aluminium Alloy 7050-T7651 | Roughing**	**1**	**1**	**2**	YES	YES	YES	YES	**1**	**1**
Intermediate Flow	Aluminium Alloy 7050-T7651 Billet	1	1	2						
Energy Flow	Machining Energy Demand | Roughing	1	1	2						
Intermediate Flow	Lubricant	1	1	2						
Intermediate Flow	Gross Product | Aluminium Alloy 7050-T7651	1	1	2						
Aggregated Process	**Numerical Machining Aluminium Alloy 7050-T7651 | Finishing**	**1**	**1**	**2**	YES	YES	YES	YES	**1**	**1**
Intermediate Flow	Aluminium Alloy 7050-T7651 Billet	1	1	2						
Energy Flow	Machining Energy Demand | Finishing	1	1	2						
Intermediate Flow	Lubricant	1	1	2						
Product Flow	Aluminium Alloy 7050-T7651 Wing Rib	1	1	2						
AVERAGE DATA QUALITY SCORE | PER INDICATOR		**1.44**	**3**	**2.78**	**1**					**1.44**
OVERALL DATA QUALITY SCORE					**1.9**					
OVERALL DATA QUALITY GRADE					**VERY GOOD**					

Scenario A : Numerically Machined Aluminium Alloy 7050-T7651

<table>
<tr><th rowspan="3">Element Type</th><th rowspan="3">Name</th><th colspan="9">Data Quality Indicator Score</th></tr>
<tr><th rowspan="2">Temporal Representativeness</th><th rowspan="2">Geographical Representativeness</th><th rowspan="2">Reliability</th><th colspan="5">Technological Representativeness</th><th rowspan="2">Completeness</th></tr>
<tr><th>Process Design</th><th>Operational Parameters</th><th>Material Grade Specificity</th><th>Process Scale</th><th>Score</th></tr>
<tr><td>Aggregated Process</td><td>Carbon Fiber Production (PAN-based) [Japan Mix]</td><td>2</td><td>2</td><td>3</td><td>YES</td><td>YES</td><td>YES</td><td>YES</td><td>1</td><td>1</td></tr>
<tr><td>Aggregated Process</td><td>Epoxy Resin Production</td><td>1</td><td>2</td><td>3</td><td>YES</td><td>YES</td><td>YES</td><td>YES</td><td>1</td><td>1</td></tr>
<tr><td>Aggregated Process</td><td>Electricity Production Mix [Netherlands]</td><td>1</td><td>2</td><td>3</td><td>YES</td><td>YES</td><td>YES</td><td>YES</td><td>1</td><td>1</td></tr>
<tr><td>Aggregated Process</td><td>Electricity from Wind Power [Netherlands]</td><td>1</td><td>2</td><td>3</td><td>YES</td><td>YES</td><td>YES</td><td>YES</td><td>1</td><td>1</td></tr>
<tr><td>Aggregated Process</td><td>Electricity Production Mix [Europe]</td><td>1</td><td>4</td><td>3</td><td>YES</td><td>YES</td><td>YES</td><td>YES</td><td>1</td><td>1</td></tr>
<tr><td>Aggregated Process</td><td>Carbon Fiber/Epoxy Prepreg Production</td><td>1</td><td>5</td><td>2</td><td>YES</td><td>YES</td><td>YES</td><td>YES</td><td>1</td><td>3</td></tr>
<tr><td>Intermediate Flow</td><td>Carbon Fiber</td><td>1</td><td>5</td><td>2</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Intermediate Flow</td><td>Epoxy Resin</td><td>1</td><td>5</td><td>2</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Energy Flow</td><td>Energy Demand | Prepregging</td><td>1</td><td>5</td><td>3</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Aggregated Process</td><td>Used Cooling | Cooled Storage</td><td>1</td><td>4</td><td>3</td><td>YES</td><td>YES</td><td>YES</td><td>YES</td><td>1</td><td>1</td></tr>
<tr><td>Aggregated Process</td><td>Natural Gas Production</td><td>1</td><td>5</td><td>3</td><td>YES</td><td>YES</td><td>YES</td><td>YES</td><td>1</td><td>1</td></tr>
<tr><td>Aggregated Process</td><td>Truck-trailer Transport | Cooled</td><td>1</td><td>5</td><td>3</td><td>YES</td><td>YES</td><td>YES</td><td>YES</td><td>1</td><td>1</td></tr>
<tr><td>Intermediate Flow</td><td>Natural Gas | Truck-trailer Consumption</td><td>1</td><td>5</td><td>3</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Intermediate Flow</td><td>Cargo | Carbon Fiber reinforced Epoxy Prepreg</td><td>1</td><td>5</td><td>2</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Aggregated Process</td><td>Isopropanol Production</td><td>1</td><td>2</td><td>3</td><td>YES</td><td>YES</td><td>YES</td><td>YES</td><td>1</td><td>1</td></tr>
<tr><td>Aggregated Process</td><td>Release Agent Production</td><td>1</td><td>5</td><td>4</td><td>YES</td><td>NO</td><td>NO</td><td>NO</td><td>4</td><td>3</td></tr>
<tr><td>Aggregated Process</td><td>Release Film/Peel Ply Production</td><td>5</td><td>1</td><td>3</td><td>YES</td><td>YES</td><td>YES</td><td>YES</td><td>1</td><td>2</td></tr>
<tr><td>Aggregated Process</td><td>Bagging Film Production</td><td>1</td><td>2</td><td>3</td><td>YES</td><td>YES</td><td>YES</td><td>YES</td><td>1</td><td>1</td></tr>
<tr><td>Aggregated Process</td><td>Breather Fabric Production</td><td>1</td><td>4</td><td>3</td><td>YES</td><td>YES</td><td>NO</td><td>YES</td><td>2</td><td>1</td></tr>
<tr><td>Aggregated Process</td><td>Vacuum Bag Sealant Tape Production</td><td>1</td><td>5</td><td>3</td><td>YES</td><td>YES</td><td>YES</td><td>YES</td><td>1</td><td>2</td></tr>
<tr><td>Aggregated Process</td><td>Compressed Air Production</td><td>1</td><td>4</td><td>3</td><td>YES</td><td>YES</td><td>YES</td><td>YES</td><td>1</td><td>1</td></tr>
<tr><td>Aggregated Process</td><td>Autoclave Curing</td><td>1</td><td>1</td><td>2</td><td>YES</td><td>YES</td><td>YES</td><td>NO</td><td>2</td><td>1</td></tr>
<tr><td>Intermediate Flow</td><td>Carbon Fiber reinforced Epoxy Prepreg</td><td>1</td><td>1</td><td>2</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Intermediate Flow</td><td>Compressed Air | Autoclave Curing</td><td>1</td><td>1</td><td>2</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Energy Flow</td><td>Energy Demand | Autoclave Curing</td><td>1</td><td>1</td><td>2</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Intermediate Flow</td><td>Isopropanol</td><td>1</td><td>1</td><td>2</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Intermediate Flow</td><td>Release Agent</td><td>1</td><td>1</td><td>2</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Intermediate Flow</td><td>Release Film/Peel Ply</td><td>1</td><td>1</td><td>2</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Intermediate Flow</td><td>Bagging Film</td><td>1</td><td>1</td><td>2</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Intermediate Flow</td><td>Breather Fabric</td><td>1</td><td>1</td><td>2</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Intermediate Flow</td><td>Vacuum Bag Sealant Tape</td><td>1</td><td>1</td><td>2</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Intermediate Flow</td><td>Gross Product | Carbon Fiber reinforced Epoxy</td><td>1</td><td>1</td><td>2</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Aggregated Process</td><td>Laminate Milling</td><td>2</td><td>5</td><td>3</td><td>YES</td><td>YES</td><td>YES</td><td>YES</td><td>1</td><td>1</td></tr>
<tr><td>Intermediate Flow</td><td>Compressed Air | Carbon Fiber reinforced Polymer Milling</td><td>2</td><td>5</td><td>3</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Energy Flow</td><td>Energy Demand | Carbon Fiber reinforced Polymer Milling</td><td>2</td><td>5</td><td>3</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Product Flow</td><td>Carbon Fiber reinforced Epoxy Wing Rib</td><td>1</td><td>1</td><td>2</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">AVERAGE DATA QUALITY SCORE | PER INDICATOR</td><td>1.35</td><td>3.23</td><td>2.94</td><td colspan="5">1.29</td><td>1.29</td></tr>
<tr><td colspan="5">OVERALL DATA QUALITY SCORE</td><td colspan="6">2.0</td></tr>
<tr><td colspan="5">OVERALL DATA QUALITY GRADE</td><td colspan="6">VERY GOOD</td></tr>
</table>

Scenario B1: Autoclave Cured Carbon Fiber reinforced Epoxy

Element Type	Name	Data Quality Indicator Score								
		Temporal Representativeness	Geographical Representativeness	Reliability	Technological Representativeness					Completeness
					Process Design	Operational Parameters	Material Grade Specificity	Process Scale	Score	
Aggregated Process	Carbon Fiber Production (PAN-based) [Japanese Mix]	2	2	3	YES	YES	YES	YES	1	1
Aggregated Process	Carbon Fiber Non-Crimp Fabric Production | Bindered	2	5	3	YES	YES	YES	YES	1	1
Aggregated Process	Epoxy Resin Production	1	2	3	YES	YES	YES	YES	1	1
Aggregated Process	Electricity Production Mix [Netherlands]	1	2	3	YES	YES	YES	YES	1	1
Aggregated Process	Electricity from Wind Power [Netherlands]	1	2	3	YES	YES	YES	YES	1	1
Aggregated Process	Diesel Production	1	3	3	YES	YES	YES	YES	1	1
Aggregated Process	Truck-trailer Transport	1	5	3	YES	YES	YES	YES	1	1
Intermediate Flow	Diesel | Truck-trailer Consumption	1	5	3						
Intermediate Flow	Cargo | Carbon Fiber Fabric	1	5	2						
Intermediate Flow	Cargo | Epoxy Resin	1	5	2						
Aggregated Process	Isopropanol Production	1	2	3	YES	YES	YES	YES	1	1
Aggregated Process	Release Agent Production	1	5	4	YES	NO	NO	NO	4	3
Aggregated Process	Polyethylene Film/Tube Production	4	4	3	YES	YES	YES	YES	1	1
Aggregated Process	Compressed Air Production	1	4	3	YES	YES	YES	YES	1	1
Aggregated Process	Fabric Preforming	1	1	2	YES	YES	YES	NO	2	1
Intermediate Flow	Carbon Fiber Fabric | Bindered	1	1	2						
Intermediate Flow	Compressed Air | Fabric Preforming	1	1	2						
Energy Flow	Energy Demand | Fabric Preforming	1	1	2						
Aggregated Process	Infusion | Resin Transfer Molding	1	1	2	YES	YES	NO	NO	3	1
Intermediate Flow	Carbon Fiber Fabric Preform	1	1	2						
Intermediate Flow	Epoxy Resin	1	1	2						
Energy Flow	Energy Demand | Resin Injection and Infusion	1	1	2						
Intermediate Flow	Gross Product | Carbon Fiber reinforced Epoxy	1	1	2						
Aggregated Process	Laminate Milling	2	5	3	YES	YES	YES	YES	1	1
Intermediate Flow	Compressed Air | Carbon Fiber reinforced Polymer Milling	2	5	3						
Energy Flow	Energy Demand | Carbon Fiber reinforced Polymer Milling	2	5	3						
Product Flow	Carbon Fiber reinforced Epoxy Wing Rib	1	1	2						
AVERAGE DATA QUALITY SCORE | PER INDICATOR		1.40	3.07	2.93	1.43					1.14
OVERALL DATA QUALITY SCORE					2.0					
OVERALL DATA QUALITY GRADE					VERY GOOD					

Scenario B2 : Resin Transfer Molded Carbon Fiber reinforced Epoxy

Element Type	Name	Data Quality Indicator Score								
		Temporal Representativeness	Geographical Representativeness	Reliability	Technological Representativeness					Completeness
					Process Design	Operational Parameters	Material Grade Specificity	Process Scale	Score	
Aggregated Process	**Carbon Fiber/Polyetherketoneketone Prepreg**	**1**	**2**	**2**	YES	YES	YES	YES	**1**	**2**
Aggregated Process	**Electricity Production Mix [Netherlands]**	**1**	**2**	**3**	YES	YES	YES	YES	**1**	**1**
Aggregated Process	**Electricity from Wind Power [Netherlands]**	**1**	**2**	**3**	YES	YES	YES	YES	**1**	**1**
Aggregated Process	**Diesel Production**	**1**	**3**	**3**	YES	YES	YES	YES	**1**	**1**
Aggregated Process	**Truck-trailer Transport**	**1**	**5**	**3**	YES	YES	YES	YES	**1**	**1**
Intermediate Flow	Diesel | Truck-trailer Consumption	1	5	3						
Intermediate Flow	Cargo | Carbon Fiber reinforced Polyetherketoneketone Prepreg	1	5	2						
Aggregated Process	**Isopropanol Production**	**1**	**2**	**3**	YES	YES	YES	YES	**1**	**1**
Aggregated Process	**Release Agent Production**	**1**	**5**	**4**	YES	NO	NO	NO	**4**	**3**
Aggregated Process	**Bagging Film Production**	**4**	**4**	**3**	YES	YES	YES	YES	**1**	**1**
Aggregated Process	**Breather Cloth Production**	**1**	**5**	**3**	NO	NO	YES	NO	**4**	**5**
Aggregated Process	**Vacuum Bag Sealant Tape Production**	**1**	**4**	**3**	YES	YES	NO	YES	**2**	**1**
Aggregated Process	**Compressed Air Production**	**1**	**4**	**3**	YES	YES	YES	YES	**1**	**1**
Aggregated Process	**Autoclave Consolidation**	**1**	**1**	**2**	YES	YES	YES	YES	**1**	**1**
Intermediate Flow	Carbon Fiber reinforced Polyetherketoneketone Prepreg	1	1	2						
Intermediate Flow	Compressed Air | Autoclave Consolidation	1	1	2						
Energy Flow	Energy Demand | Autoclave Consolidation	1	1	2						
Intermediate Flow	Isopropanol	1	1	2						
Intermediate Flow	Release Agent	1	1	2						
Intermediate Flow	Bagging Film	1	1	2						
Intermediate Flow	Breather Cloth	1	1	2						
Intermediate Flow	Vacuum Bag Sealant Tape	1	1	2						
Intermediate Flow	Gross Product | Carbon Fiber reinforced Polyetherketoneketone	1	1	2						
Aggregated Process	**Laminate Milling**	**2**	**5**	**3**	YES	YES	YES	YES	**1**	**1**
Intermediate Flow	Compressed Air | Carbon Fiber reinforced Polymer Milling	2	5	3						
Energy Flow	Energy Demand | Carbon Fiber reinforced Polymer Milling	2	5	3						
Product Flow	Carbon Fiber reinforced Polyetherketoneketone Wing Rib	1	1	2						
AVERAGE DATA QUALITY SCORE | PER INDICATOR		**1.307**	**3.38**	**2.92**	**1.54**					**1.54**
OVERALL DATA QUALITY SCORE					**2.1**					
OVERALL DATA QUALITY GRADE					**GOOD**					

Scenario C1 : Autoclave Consolidated Carbon Fiber reinforced PEKK

Element Type	Name	Data Quality Indicator Score								
		Temporal Representativeness	Geographical Representativeness	Reliability	Technological Representativeness					Completeness
					Process Design	Operational Parameters	Material Grade Specificity	Process Scale	Score	
Aggregated Process	**Carbon Fiber/Polyetherketoneketone Prepreg Production**	**1**	**2**	**2**	YES	YES	YES	YES	**1**	**2**
Aggregated Process	**Electricity Production Mix [Netherlands]**	**1**	**2**	**3**	YES	YES	YES	YES	**1**	**1**
Aggregated Process	**Electricity from Wind Power [Netherlands]**	**1**	**2**	**3**	YES	YES	YES	YES	**1**	**1**
Aggregated Process	**Diesel Production**	**1**	**3**	**3**	YES	YES	YES	YES	**1**	**1**
Aggregated Process	**Truck-trailer Transport**	**1**	**5**	**3**	YES	YES	YES	YES	**1**	**1**
Intermediate Flow	Diesel | Truck-trailer Consumption	1	5	3						
Intermediate Flow	Cargo | Carbon Fiber reinforced Polyetherketoneketone Prepreg	1	5	2						
Aggregated Process	**Isopropanol Production**	**1**	**2**	**3**	YES	YES	YES	YES	**1**	**1**
Aggregated Process	**Release Agent Production**	**1**	**5**	**4**	YES	NO	NO	NO	**4**	**3**
Aggregated Process	**Compressed Air Production**	**1**	**4**	**3**	YES	YES	YES	YES	**1**	**1**
Aggregated Process	**Automated Tape Laying**	**1**	**1**	**2**	YES	YES	YES	NO	**2**	**1**
Energy Flow	Energy Demand | Automated Tape Laying	1	1	2						
Aggregated Process	**Prepreg Preforming**	**1**	**1**	**2**	YES	YES	YES	NO	**2**	**1**
Intermediate Flow	Carbon Fiber/Polyetherketoneketone Prepreg	1	1	2						
Energy Flow	Energy Demand | Prepreg Preforming	1	1	2						
Intermediate Flow	Compressed Air | Prepreg Preforming	1	1	2						
Intermediate Flow	Carbon Fiber/Polyetherketoneketone Preform	1	1	2						
Aggregated Process	**Press Consolidation**	**1**	**1**	**2**	YES	YES	YES	YES	**1**	**1**
Intermediate Flow	Release Agent	1	1	2						
Intermediate Flow	Isopropanol	1	1	2						
Intermediate Flow	Carbon Fiber reinforced Polyetherketoneketone Preform	1	1	2						
Intermediate Flow	Compressed Air | Autoclave Consolidation	1	1	2						
Energy Flow	Energy Demand | Autoclave Consolidation	1	1	2						
Intermediate Flow	Gross Product | Carbon Fiber reinforced Polyetherketoneketone	1	1	2						
Aggregated Process	**Laminate Milling**	**2**	**5**	**3**	YES	YES	YES	YES	**1**	**1**
Intermediate Flow	Compressed Air | Carbon Fiber reinforced Polymer Milling	2	5	3						
Energy Flow	Energy Demand | Carbon Fiber reinforced Polymer Milling	2	5	3						
Product Flow	Carbon Fiber reinforced Polyetherketoneketone Wing Rib	1	1	2						
AVERAGE DATA QUALITY SCORE | PER INDICATOR		**1.08**	**2.75**	**2.75**	**1.42**					**1.25**
OVERALL DATA QUALITY SCORE					**1.8**					
OVERALL DATA QUALITY GRADE					**VERY GOOD**					

Scenario C1 : Autoclave Consolidated Carbon Fiber reinforced PEKK

B

Tabulated Normalized Results for Life Cycle Impact Assessment

	SCENARIO [IMPACT NORMALIZED TO MAXIMUM]				
IMPACT CATEGORIES	NUMERICALLY MACHINED ALUMINUM ALLOY 7050-T7651	AUTOCLAVE CURED CARBON FIBER REINFORCED EPOXY	RESIN TRANSFER MOLDED CARBON FIBER REINFORCED EPOXY	AUTOCLAVE CONSOLIDATED CARBON FIBER REINFORCED PEKK	PRESS CONSOLIDATED CARBON FIBER REINFORCED PEKK
Acidification	1	0.163934426	0.197540984	0.421311475	0.270491803
Climate change	1	0.609302326	0.618604651	0.897674419	0.6
Ecotoxicity, freshwater	0.08950495	0.056534653	0.093960396	1	0.681188119
Eutrophication, freshwater	0.001704545	0.004502841	0.005042614	1	0.683238636
Eutrophication, marine	0.943005181	0.402072539	0.441968912	1	0.668393782
Eutrophication, terrestrial	1	0.411055276	0.452763819	0.026180905	0.002336683
Human toxicity, cancer	0.346285714	0.212571429	1	0.144	0.08
Human toxicity, non-cancer	1	0.463366337	0.378712871	0.658415842	0.004440594
Ionising radiation, human health	1	0.257912458	0.203367003	0.017542088	0.002683502
Land use	0.676229508	1	0.614754098	0.717213115	0.314344262
Ozone depletion	4.30839E-05	0.000478458	1.61451E-05	1	0.684807256
Particulate matter	1	0.086705202	0.13699422	0.04566474	0.001375723
Photochemical ozone formation - human health	1	0.393053016	0.436928702	0.714808044	0.47166362
Resource use, fossils	1	0.558510638	0.561170213	0.819148936	0.54787234
Resource use, minerals and metals	1	0.005601966	0.006756757	0.01036855	0.001722359
Water use	1	0.180417755	0.835509138	0.14308094	0.054046997

Figure B.1: Tabulated Normalized Results for Life Cycle Impact Assessment - Cradle-to-Gate

	SCENARIO [IMPACT NORMALIZED TO MAXIMUM]				
IMPACT CATEGORIES	NUMERICALLY MACHINED ALUMINUM ALLOY 7050-T7651	AUTOCLAVE CURED CARBON FIBER REINFORCED EPOXY	RESIN TRANSFER MOLDED CARBON FIBER REINFORCED EPOXY	AUTOCLAVE CONSOLIDATED CARBON FIBER REINFORCED PEKK	PRESS CONSOLIDATED CARBON FIBER REINFORCED PEKK
Acidification	1	0.981412639	0.983271375	0.986988848	0.983271375
Climate change	1	0.994011976	0.994011976	1	0.994011976
Ecotoxicity, freshwater	0.946107784	0.94011976	0.946107784	1	0.982035928
Eutrophication, freshwater	0.038303694	0.040902873	0.041450068	1	0.69493844
Eutrophication, marine	0.995575221	0.991150442	0.991150442	1	0.995575221
Eutrophication, terrestrial	1	0.995951417	0.995951417	0.991902834	0.991902834
Human toxicity, cancer	0.963934426	0.954098361	1	0.950819672	0.947540984
Human toxicity, non-cancer	1	0.991666667	0.991666667	1	0.983333333
Ionising radiation, human health	1	0.609236234	0.579040853	0.481349911	0.474245115
Land use	0.903186275	1	0.884803922	0.914215686	0.794117647
Ozone depletion	6.32653E-05	0.000498866	3.62812E-05	1	0.684807256
Particulate matter	1	0.920792079	0.925742574	0.915841584	0.915841584
Photochemical ozone formation - human health	1	0.995176849	0.995176849	0.996784566	0.995176849
Resource use, fossils	1	0.995594714	0.995594714	1	0.995594714
Resource use, minerals and metals	1	0.044208038	0.045390071	0.04893617	0.040661939
Water use	1	0.49025974	0.897727273	0.465909091	0.410714286

Figure B.2: Tabulated Normalized Results for Life Cycle Impact Assessment - Cradle-to-End of Service