Master of Science Thesis

Comparative Study of the Environmental Sustainability of Aluminium and Composite Aerostructures, with a Case Study of a Wing Rib

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Comparative Study of the Environmental Sustainability of Aluminium and Composite Aerostructures, with a Case Study of a Wing Rib

by

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Preface

This report documents the work I performed over the past nine months, marking the end of my master degree studies in aerospace engineering. The main focus of the study was to create a preliminary comparative tool for different materials used in aerospace engineering, which can be further expanded, ultimately aiming for a more sustainable future of aerospace structures. The project was an equally challenging and rewarding one, switching from intensive searches for databases and general process data, to discussions with industry professionals about the relevance and feasibility of a structure's mass production and lastly to the application of the data to a case study. The topic of aerostructures (both metallic and composite) and sustainability aligned perfectly with my interests, helping me enjoy my time working on this project and gaining valuable knowledge for my future career as an aerospace engineer.

I would like to thank my supervisors, ir.Jos Sinke and ing.Marc Koetsier for their constant support throughout the thesis project, for their positive attitude and their feedback which helped me write this report. I would also like to thank Dr.ir.Thomas de Bruijn, for his guidance and useful feedback on my data acquisition stage and report, and Arnt Offringa, GKN Fokker Hoogeveen Global Technology Centre director, for his presence at important stages of my thesis, for his advice and in-depth questions which helped me ensure the quality of the data present in this report. Lastly, I would like to address a large thank you for their time and insight, to everyone from the GKN Aerospace team with whom I have interacted throughout my project, and without whom finding the required data would not have been possible.

Within my personal circle, a thank you goes as well to all of my friends with whom I have studied for the past 5 years, for their support and for making my university experience better altogether. Last but not least, a wholehearted thank you to my parents, who have supported me at every step of the way, for their patience and their invaluable advice and guidance. For that, I cannot thank you enough.

Andrei Stefanidi
Delft, October 2022

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Summary

This chapter provides a short summary of the information covered within this thesis. This project was divided into three main stages. The first stage was the literature study, during which the student is required to gather as much background information as possible about the topic and become familiar with the information which is needed for completing the project. The second stage, is the data acquisition stage, which involved the collection of a large number of data, including verification when possible. The third and last stage started after the midterm review of the project, and it consisted of applying the collected data and slowly closing in towards a result. The motivation of the thesis consisted of the rapid development of technology as a means of improving the quality of life, but with the downside of it having negative impacts on the environment. The end goal was to analyse different aerostructures from an environmental sustainability standpoint, and determine which ones would be better suited for the aircraft of the future, using the case study of a wing rib as an example.

For the data collection, the material flows for each of the aluminium alloys selected (Al7075 T73 and Al7050 T7451) as well as for the different composites (thermoset Epoxy CFRP with prepreg manufacturing and thermoset Epoxy CFRP with RTM manufacturing, and thermoplastic PEKK CFRP with out of autoclave consolidation manufacturing) are generated. Each material flow covers the different life stages of the material, starting from the raw material production, followed by the transport to the factory, the manufacturing route selected with its individual steps, the operational phase and lastly the recycling stage at the end of life of the component. Each of these flows are then considered separately and numbers are found for the energy consumption and the CO_2-eq emissions for each individual step, with summary tables presented at the end of each section.

Using these numbers, the life cycle assessment for a wing rib within the Wing of Tomorrow program is performed. Based on the structural component selected, its function and life duration, the following functional unit is selected: *"Aircraft wing structural component responsible for giving the geometry of the wing and carrying the loads both during ground and air operation of an A320 Neo aircraft, over an average lifetime of 30 years"*. The LCA boundaries are set strictly to the processes involved in the raw material production, followed by the transport stage, manufacturing, operational life and lastly recycling, thus ignoring the source of the inputs required for these processes such as additional machinery needed to produce the extraction tools, the production machinery, fuel required for those, etc.

Overall, it was found that using the processes and the assumptions which can be found throughout chapter 2, chapter 3 and also in Appendix A, the lowest energy consumption appears in sheet metal forming processes, followed by the RTM processes for Epoxy CFRP ribs, out of autoclave consolidation (hot press consolidation) for PEKK CFRP ribs, Epoxy CFRP prepreg ribs and lastly the aluminium machined ribs which require significantly more energy than all other processes. Additionally, the CO_2-eq emissions follow the same trend. These comparisons were done first by excluding the operational phase of the life cycle of the components, and then by including it. It was noticed here that due to the long life expectation of an aircraft (roughly 30 years), the operational phase makes every other life phase negligible both in terms of energy consumption and CO_2-eq emissions. Overall, a reduction in energy consumption and CO_2-eq emissions of up to 42% is seen in the case of composites compared to aluminium structures purely based on the difference in the rib weight (from 3.66 kg for aluminium to 2.10 kg for composites). A discussion is made here as well about the possibility of further improving the processes by integrating a 100% recyclability rate for the thermoplastic materials, and what this would entail for the results of this study as well as further ones concerned with the structures created using said recycled material. A short sensitivity analysis was then performed on some of the assumptions which have raised questions throughout the project, and some of which were thought to have potential for affecting the results. The first element here was the use of adhesive bonds in the case of sheet formed aluminium ribs. By removing this process, the energy usage was calculated to decrease by up to 12% and a similar number is seen as well in the case of the CO_2 emissions. These changes were with respect to the total processing energy, while if the entire life cycle is considered, the change is negligible. The next element in the analysis was the storage time of the thermoset composites. The original duration was of 18 months, and this was varied to 12 months and 6 months. In this case, changes of 33% and

66% were observed respectively. Once again, if the changes are analysed in the bigger picture (looking at the whole production phase), only a change of 0.1% is observed, which would obviously decrease much further if the operational phase is included in the mix too, thus making the storage time negligible as well. The third element was the weight of the composite ribs, as it was originally assumed that they would all have the same weight. Performing calculations based on the densities of the resins and the fibre fractions, it was found that the change in weight is only of 2%, and therefore a recalculation of the energy and CO_2 emissions for the processes involving these materials was not required. A final aspect considered is the possibility for the future of changing from conventional fuels to hydrogen or electric propulsion. This is done in a more qualitative manner rather than quantitative since it does not make the main focus of this thesis. It is interesting to mention however due to the results of the study which suggest the operational phase has the most significant impact on the environment, and therefore changing to ”emission-free” operational fuels could improve this for the future. Based on this discussion it is briefly suggested that while these fuels do provide lower CO_2 emissions, in order for vehicles to fully be considered ”emission-free”, an analysis would need to be performed on the background energy sources and processes as well.

Finally, it was recommended for improvement of the results that the study of individual stages presented within this thesis is done separately, in an in-depth manner, including prototype manufacturing such that primary data is available for all steps, rather than having to rely heavily on secondary data. Additionally, based on the sensitivity analysis performed, it was also suggested that a study of some of the processes which were considered negligible for this study to be taken into account and that the conversion factor used for the operational phase to convert from energy usage to GHG emissions to be checked independently as well. This conversion factor was found to be larger in the case of the world electricity mix (0.131 kg/MJ) than in the case where only conventional fuels are used (0.072 kg/MJ), and it is therefore considered rather peculiar and worth studying separately. The last mentioned improvement has to do with the discussion of alternative fuels which was done in the results and discussion chapter. Since these were only discussed on a qualitative level, it could be important to also have a look at them from a quantitative point of view, and determine the actual effect that switching to such propulsion systems would have on the environmental sustainability in aviation.

Contents

List of Figures

List of Tables

Nomenclature

Abbreviations

Abbreviation	Definition
LCA	Life cycle assessment
LCI	Life cycle inventory analysis
LCIA	Life cycle impact assessment
WoT	Wing of Tomorrow
VSM	Value stream mapping
GHG	Greenhouse gasses
GWP	Global warming potential
GFRP	Glass fibre reinforced polymer
CFRP	Carbon fibre reinforced polymer
FML	Fibre metal laminate
RTM	Resin transfer moulding
NDI	Non-destructive inspection
TSA	Sulphuric-tartaric anodising
BTU	British Thermal Units
ATL	Automatic tape laying
AFP	Automatic fibre placement
OOAC	Out of autoclave consolidation

Symbols

Symbol	Definition	Unit
d	Distance travelled	[km]
D	Drag	[-]
g	Gravitational acceleration	[m/s^2]
H	Flight altitude	[m]
L	Lift	[-]
m	Mass	[kg]
ρ	Density	[kg/m^3]

1 Introduction

This chapter is meant to give a general introduction to the thesis as a whole. This includes a description of the thesis within the MSc. programme at TU Delft, the motivation for choosing the present topic, background information gathered in the first stages of the thesis and lastly the objectives set for the project.

1.1. Thesis project and report structure

This thesis has been conducted as a mandatory component of the Aerospace Structures and Materials Master of Science program at the TU Delft. The thesis project consists of two main components. The first one is the literature study in which the student researches the chosen topic and establishes a basic understanding of the concepts required as well as the work which has been conducted in the area and the state of the art of the topic. The second part is the thesis work in itself, where the objective of the thesis is addressed using the gathered knowledge together with further detailed research where needed. The structure of this report has been selected such that these two components are efficiently shown for the thesis topic at hand.

First, for the introduction to the project, the motivation for choosing the topic is addressed, followed by a summary of the different aspects which were researched during the literature phase. This literature review includes information on sustainability as an area of interest, the materials used in aerospace structures and which are relevant for the study at hand, some general information on manufacturing possibilities for said materials and information on life cycle assessments and value stream mapping. In addition to these, the background regarding the Wing of Tomorrow program by Airbus (relevant to the case study) is also provided. Lastly, the objectives for the thesis are laid down in order to have a clear description of what it is that is expected from the results of this study.

Next, chapter 2 presents the data collection step of the project. Here, the material flows are first generated for all the different processes considered for manufacturing the wing rib of the case study selected. The data collection itself is divided into different sections, one for each processing option, since all of them have different energy requirements based on the steps taken.

With the data documented, the next step is to look at the life cycle assessment (LCA) for the case study considered. This is done in chapter 3. This chapter is divided into sections based on the steps taken in setting up an LCA: defining the goal and scope, performing the inventory analysis, impact assessment and lastly interpreting and evaluating the results. Once again the inventory analysis is divided into subsections based on the different processes considered.

Lastly, the results are all presented and discussed in chapter 4, followed by a conclusion and proposed future steps in chapter 5. Additionally, for convenience purposes, Appendix A presents all the assumptions made throughout the report.

1.2. Motivation for thesis topic

Over the years, technology has been advancing at an increasing rate in many, if not all, of the areas of human activity, with a main purpose of increasing the overall quality of life of the increasing population. One of these areas is also that of transportation, where research is constantly conducted in order to design vehicles which are faster, more efficient and very importantly more sustainable than in the past.
Taking the example of aircraft, some of the research conducted involves the use of novel materials for creating structures which are lighter and as strong or even stronger than current ones, the use of alternative fuels which could replace current aviation fuels in order to reduce unwanted emissions, or even attempts at modifying the aerodynamics of an aircraft in order to increase its efficiency. These are of course, only a small number of examples covering interests for further improving today's flying technology.
The topic of this thesis looked at the first example, the use of novel materials, specifically composite materials. These are materials which have gained more popularity over the years, not only in the aeronautical domain, but also in automotive, naval, and construction sectors. The importance of studying the sustainability of these materials compared to current metal structures comes from a combination of factors. One of these is the energy usage for producing the materials in the first place. Since sustainability starts with the extraction of raw materials and ends with the recyclability of the final parts, it is important to consider all of the intermediate stages when doing an analysis for a material, prior to switching to mass manufacturing and replacement of all current selected materials. Waste is another factor, and the importance of considering it can be expressed using predictions regarding material waste in the upcoming years. When looking at carbon fibre reinforced polymers, it is estimated that 683,000 tons of waste will be produced in Europe in 2025 [1] with aeronautics alone being responsible for at least 41,000 tons [2]. As the manufacturing of parts out of composite materials is done worldwide, the numbers for the estimated waste would grow significantly if looked at on a global scale.
Overall, a study of the difference between materials is required in order to be able to determine which options are most sustainable, thus leading to the topic for this thesis.

1.3. Background and literature review

This section gives an overview of the information gathered during the literature study conducted at the beginning of this project, as well as additional background information regarding the Wing of Tomorrow project of Airbus for the case study.

1.3.1. Sustainability

Sustainability is a complex topic that includes a multitude of aspects, as mentioned before. These include ensuring the low weight of a structure, leading to lower fuel consumption and GHG emissions, processing of materials, considering the scarcity of certain materials and also recycling. Considering the manufacturing of parts, one must consider their different life stages starting from material production (mining of raw materials/resources), and ending with the end of life of the part/structure where one must choose between recycling options or discarding the part. Before starting to discuss these elements, it is important to give a definition of sustainability that will help guide the study. There are many different definitions for sustainability, but one which is generally agreed upon defines it as development that "[meets] the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland 1987)[3].

Sustainability is typically divided into 3 pillars, including the social sustainability, environmental sustainability and the economical sustainability, with each of these three being equally important since a product can not be defined as being sustainable if one of these pillars is neglected [49]. The topic of the project at hand is only regarding the environmental sustainability of the structures. Even within environmental sustainability, there are different aspects that can be considered such as: energy usage, greenhouse gases, water consumption and waste production. Due to the complexity of sustainability as a whole and the time required for data collection, the main focus for this study was limited to the

[1] https://static1.squarespace.com/static/5a60c3cc9f07f58443081f58/t/61a1042e01d66c32ef829583/1637942321543/Understanding+Composites_Final.pdf

[2] https://etipwind.eu/files/reports/ETIPWind-How-wind-is-going-circular-blade-recycling.pdf

[3] https://www.un.org/en/academic-impact/sustainability

energy usage followed by the CO_2 emissions resulting from it. Energy is used to some extent in all processes involved in the manufacturing of a part or assembly, from the extraction of raw materials, to the processing of the semi-finite parts and then the final part/assembly followed by its end-of-life management. It is worth noting that some processes may be more energy intensive than others, and small energy consumers will be present at every stage, and therefore it is important to define boundaries on which consumers are taken into account and which ones are omitted/neglected. This must be done since considering every consumer down to smallest one is not only very difficult, but also unrealistic to strive for from a practical perspective. The process of boundary setting will be discussed in the life cycle assessment section, and any further assumptions will be presented clearly throughout the data collection process presented in chapter 2. In many of the cases presented throughout this report, energy refers to the electrical energy consumed by machinery, or energy obtained directly by means of burning of fuels (e.g. during the operational phase of the part's life). Of course, the electrical energy comes at its turn from a variety of sources, such as fuel burning, renewable (green) sources (i.e. hydro, wind, solar), or nuclear plants. The source of the energy will typically affect the estimated CO_2 emissions. It is first important to mention that the values reported here are for CO_2 equivalent (CO_2-eq). When referring to greenhouse gasses (GHG), there is more than CO_2 which affects negatively the environment. A typical unit of measure employed in order to take into account the effect of the gasses emitted is the CO_2-eq. This is done by looking at the global warming potential (GWP), with each gas emission being converted to equivalent amounts of CO_2 that would have the same GWP[4]. The CO_2 footprint (amount of CO_2 produced per MJ of energy used), can be estimated based on the type of energy used as mentioned previously. Predefined ratios exist for all the countries around the world, including the averages per continent and also worldwide. These ratios are determined based on the electricity mix in the respective countries (mix of fossil fuel, nuclear and renewable sources) [5]. The equation used to perform this conversion is the following [3]:

$$\mathrm{CO_2\ footprint\ [kg/MJ]} = \frac{\text{Fossil fuel proportion}}{\text{Conversion efficiency}} \cdot \mathrm{CO_2\ conversion\ factor\ [kg/MJ]} \tag{1.1}$$

where the fossil fuel proportion and conversion efficiencies are values provided in databases such as that of CES EduPack, and so is the conversion factor used for the carbon dioxide, provided as 0.071 kg/MJ [3] for these calculations.
Of course, another important aspect when talking about sustainability is as mentioned the waste generated, and although this is not the main focus of this project, any notable sources of waste will be pointed out during the data collection for the various processes used as well as at any other stage of the part's life cycle.

1.3.2. Materials in aerospace structures

Materials used in aerospace structures are subject to a number of requirements, with a very important one being to possess high specific mechanical properties. In other words, these materials must be capable to resist large loads being applied under different conditions while also being lightweight. A light structure will result in a sequence of changes in the design that further reduce the weight of the aircraft, a phenomenon sometimes referred to as a snowball effect. A lighter structure will require less energy to be transported from one point to another, therefore requiring smaller (and lighter engines), as well as lower amounts of fuel, thus further affecting the weight of the aircraft, the aerodynamics (which in turn affect the drag and thus once again the fuel required per flight), and the process repeats itself. Conversely, the opposite is also true, with any increase in weight of a component resulting in a further increase in the overall aircraft weight from multiple sources. The standard practice for the moment still remains the use of metals for a large number of structures, due to their favourable properties, defined part manufacturability and thereby the familiarity that most industries have with their use. An example of metal used in aerospace engineering is aluminium, with a multitude of alloys being available based on the specific requirements of the part being designed. Aluminium as a material is obtained from bauxite ore, which is first refined into alumina, which is then smelted to obtain pure aluminium, with a conversion ratio mentioned in older literature to be of roughly 4:2:1 [55]. Newer technology reports based on improved processes with higher efficiencies (96%) suggest that 1 tonne of aluminium can be

[4] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Carbon_dioxide_equivalent
[5] http://support.grantadesign.com/resources/cesedupack/2019/help/html/eco/ecodata_countryelectricitymix.htm

obtained from 2.7 tonne of bauxite, thus reducing the ratio from 4:1 to 2.7:1 [8]. The bauxite is refined through the Bayer process, during which the ore is mixed with caustic soda and heated under pressure, allowing the aluminium to dissolve in the solution and be separated from other impurities. An example of important output for this process is the red mud, which is considered hazardous to the environment, and specifically to water and soil [48]. The next step is to go through the Hall-Héroult process [8], where a solution is formed by dissolving the aluminium oxide (alumina) from the previous step into cryolite. Current is then passed through said solution, resulting into aluminium and CO_2. Once pure aluminium is obtained, the last step is to create the alloys needed for different applications. Wrought aluminium alloys are divided into 8 groups referred to as series, with the first being the 1xxx series (pure aluminium). The remaining series are based on the dominant material used for the alloying process of aluminium. A table with these can be seen in Figure 1.1[50].

Alloy Series	Principal Alloying Element
1xxx	99.000% Minimum Aluminum
2xxx	Copper
3xxx	Manganese
4xxx	Silicon
5xxx	Magnesium
6xxx	Magnesium and Silicon
7xxx	Zinc
8xxx	Other Elements

Figure 1.1: Aluminium alloy series [50]

For wing rib manufacturing at GKN Fokker, two specific alloys were looked at during this project, Al7075 T73, and Al7050 T7451. The 7xxx series of aluminium indicates that the alloys are predominantly made by using zinc as the main alloying material, while the T73 and T7451 refer to the different temper used. Similar to the aluminium series, the tempers are divided into different categories based on the processes used to improve the properties of the aluminium alloy. A summary of these categories can be seen in Figure 1.2[50].

T1 - Naturally aged after cooling from an elevated temperature shaping process, such as extruding.
T2 - Cold worked after cooling from an elevated temperature shaping process and then naturally aged.
T3 - Solution heat-treated, cold worked and naturally aged.
T4 - Solution heat-treated and naturally aged.
T5 - Artificially aged after cooling from an elevated temperature shaping process.
T6 - Solution heat-treated and artificially aged.
T7 - Solution heat-treated and stabilized (overaged).
T8 - Solution heat-treated, cold worked and artificially aged.
T9 - Solution heat treated, artificially aged and cold worked.
T10 - Cold worked after cooling from an elevated temperature shaping process and then artificially aged.

Figure 1.2: Alloy tempering categories [50]

Another group of materials which are used in aerospace applications are composite materials, and specifically fibre reinforced polymers. These materials have started being used already some 50 years ago, mostly in secondary structures of military aircraft such as the F15 [37]. Due to more recent developments in technology and knowledge of the behaviour of such materials, it is now also possible to create primary structures for aircraft, not only military but also civil. Two examples are Boeing 787 and Airbus A350, with roughly 50% (by weight) of the structures (including primary structures) being made out of composites. A visual representation of material distribution in a Boeing 787 can be seen in Figure 1.3 [32]. Other more complex examples of materials can also be found, with the A380 containing parts made out of GLARE [22], an aluminium alloy - glass fibre reinforced polymer (GFRP) composite

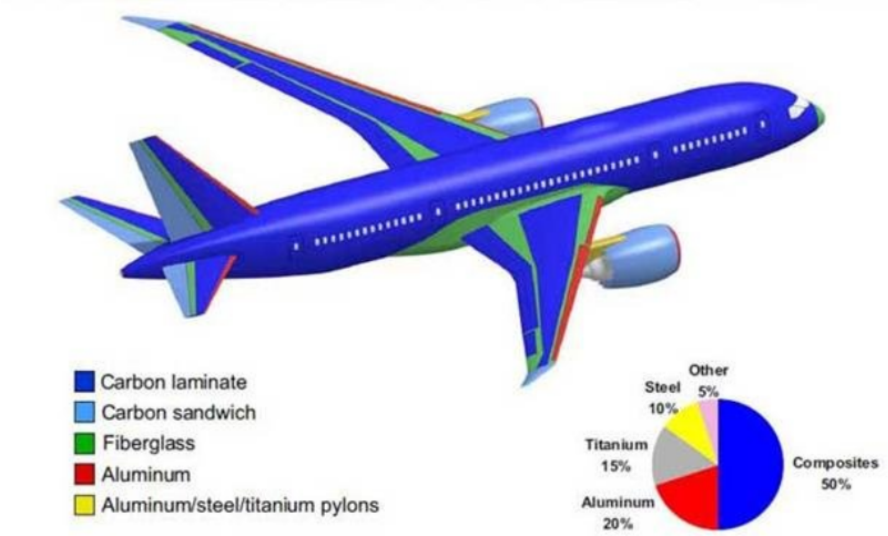

Figure 1.3: Materials used in a Boeing 787 [32]

referred to as a fibre metal laminate (FML). Just as a disclaimer, this is a very particular type of composite which uses a combination of standard composite materials and metal, and is not part of this study in itself, but rather used only as an example of the use of such materials in the aerospace industry. Designing with composites involves a number of choices that one must make, similar to the choices between different alloys or temperings when it comes to metal parts. One of the aspects that one has to choose between is the use of thermoplastic or thermoset matrices, referring to the resin used. The main difference between these two types of resin comes from the phenomena occurring during production for the two. Thermoset materials undergo curing, a chemical reaction in which crosslinks are formed between the polymer molecules giving the polymer a definitive shape/structure which can not be reversed. Attempts to melt the material again will result in damage of the polymer. Thermoplastic materials on the other hand do not cure, which allows them to be remelted and reshaped. This gives thermoplastics great potential for recycling and reuse.
Another choice that has to be made is about the reinforcing fibres used. Common fibres are carbon and glass, although others such as natural fibres (banana fibre, cotton, flax, hemp, etc.), polymer fibres (acrylic, aramid, etc.) are also available, although not commonly used in aerospace structural applications. The focus during this project was on carbon fibre reinforced polymers (CFRP). The chosen polymers were Epoxy for the thermoset version of the material, and PEKK (polyetherketoneketone) for the thermoplastic one.

Starting with the carbon fibres, these are produced from an organic polymer known as polyacrylonitrile (PAN) [26]. First, this polymer undergoes spinning, a process through which the fibres are formed. Due to their thermal instability, these fibres must be treated chemically such that they do not get damaged during subsequent processes involving high temperatures. The stabilisation takes place in ovens, heated chambers or by use of hot air/rollers where the goal is to trap oxygen into the polymer [26]. After stabilisation, the fibres are carbonised. This process aims to form the carbon crystals that give the fibres their mechanical properties. This process is conducted at temperatures of up to 3000°C. In order to avoid damaging the fibres, this process is conducted in special furnaces, in the absence of oxygen. Surface treatments are required after this process in order to ensure that adequate bonding can be achieved with the resin during part manufacturing. The treatments are typically achieved by passing the fibres through air or ozone. This ensures the bonding also by making the surface rougher (due to the chemical reaction with oxygen). Sizing is the last step required, which involves covering the fibres in a thin film that protects them during handling and winding. This film is typically a resin such as Epoxy that is also compatible with the resin the fibres will later be infused with during manufacturing [26]. For the resins, they are typically produced by combining chemical compounds. The production of these chemical compounds is often intellectual property and therefore kept secret. As a result it was considered outside of the scope of the thesis, and therefore not much detail will be given about them.

Epoxies are obtained from the reactions of bisphenol-A and epichlorohydrin [19], with bisphenol-A being obtained from products originating from petroleum [53]. It is also important to mention that epoxies can come in a one-part option which requires cold storage in order to prevent premature curing, or in a two-part alternative where the curing process only commences with the addition of curing agents such as aminoamides, polyamines, or phenolic compounds [25], therefore being easier to handle and store until part manufacturing. The last component which will be mentioned here is the only thermoplastic resin mentioned, PEKK. This is once again a chemical compound obtained from a mixture of diphenyl ether, terephtaloyl chlorides, aluminium chlorides and nitrobenze [2]. This time however, the end product will not start curing (as is the case for epoxies) after the constituents are joined since it is a thermoplastic resin. Once again, the source of these compounds is considered outside of the scope of the thesis and therefore will not be discussed further.

1.3.3. Part manufacturing and assembly of aerospace structures

This subsection will present some of the manufacturing and assembly technologies used within aerospace engineering. The discussion will however be only a summary of the work done for the literature study report [47]. Starting with aluminium part manufacturing, there are two main manufacturing routes which were chosen for this project. The first is machining the aluminium blocks into the desired shape, and the second is sheet metal forming.

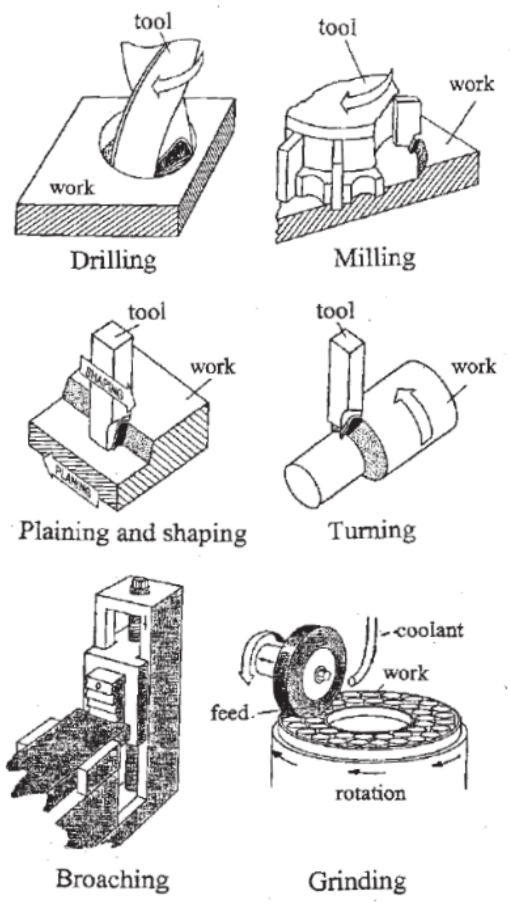

Figure 1.4: Machining processes [31]

Machining is a manufacturing method which includes a number of different processes such as drilling, grinding, or milling. Machining a part will typically require two steps, the coarse machining where the overall goal is to remove a large quantity of material from the starting block at a high rate, followed by a fine machining stage where the small adjustments are made so that the final shape of the part is obtained with a degree of accuracy[29]. An illustration of different machining processes can be seen in Figure 1.4 [31]. All machining processes are similar in that they remove material under the form of chips, not to be confused with shearing processes where larger pieces are cut off in one go (using for instance punches, or scissors) [29]. When it comes to machining, the amount of chips removed can be significant. During discussions with specialists in metal processing from GKN Fokker, estimates of material removed as chips of up to 95% of the original starting block were reported **[Jos Thoolen, personal communication, 13.06.2022]**. Therefore, an important consideration is whether these chips can be collected and recycled. When working with aluminium alloys, and especially the ones selected previously for this assignment, recycling of these chips can definitely be achieved. Overall, it is estimated that up to 75% of the aluminium ever produced is still used today as a result of its good recyclability [8].

As mentioned before, a second alternative for manufacturing aluminium ribs could be through sheet forming. This is a less common route, from a number of reasons. For example, wing ribs can take complex cross-sectional shapes, meaning that as opposed to machining, manufacturing using sheets will be in most cases impossible to do in one go. Typically, two symmetrical halves will be manufactured and then connected to obtain the final shape and web stiffening elements will need to be added separately. Despite being less efficient (labour-wise, time-wise and potentially cost-wise), this manufacturing route was still taken into consideration for this assignment since the interest was to see whether it would have a chance of being environmentally more sustainable compared to its counterparts. Forming of sheets can be achieved as well through a number of different processes, including rolling, roll forming, or by use of various presses (either simple ones like in press-brake bending or rubber presses). For these press processes, the metal sheet is placed onto a die and the press deforms it into the desired shape, as can be seen in Figure 1.5 [36].

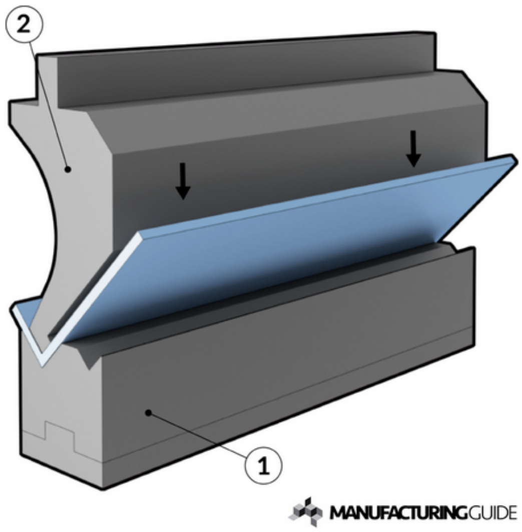

Figure 1.5: Press brake bending process [36]

Variations in this process can be seen depending on the die used for deforming the part, not only from the point of view of its geometry, but also the material it is made of. For parts which are surface treated and painted prior to the deformation, a rubber die may be required in order to protect the surface finish. An important variation here is rubber forming which is commonly used especially for parts such as wing ribs. For this process, the pressure can be applied with the use of fluid as seen in Figure 1.6 or a solid rubber panel as in Figure 1.7 [45].

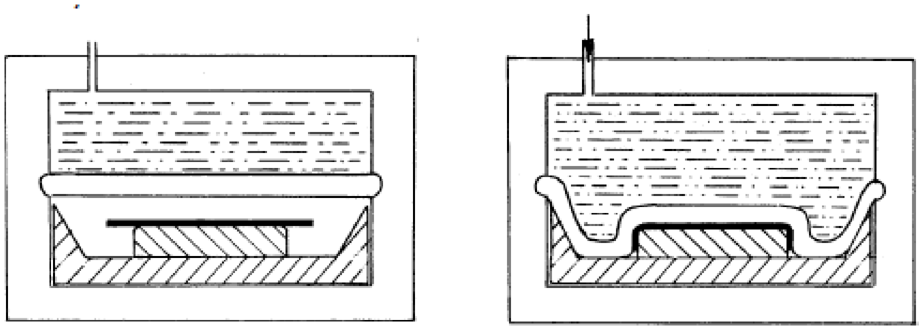

Figure 1.6: Fluid cell rubber forming [45]

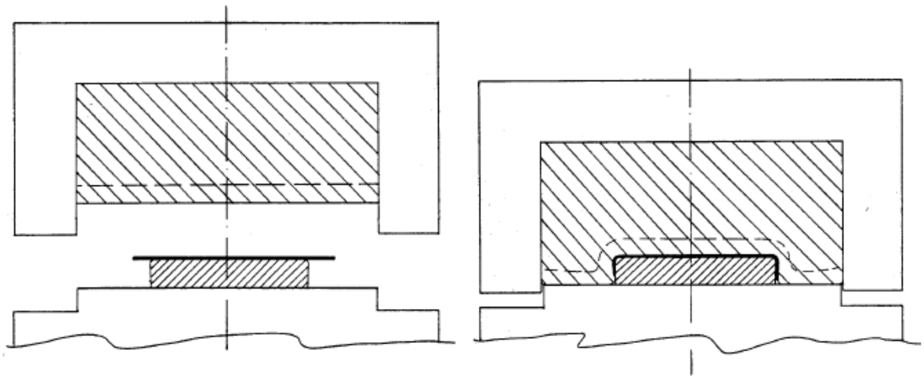

Figure 1.7: Solid rubber pad forming [45]

Rolling is another important process to consider here, since in order to use a press, the metal has to be turned into sheets of various thicknesses. This process can be conducted either with the addition of heat or without (hot vs cold rolling), although, in most cases hot rolling is preferred [34]. A representation of this can be seen in Figure 1.8 [34], where a thin metal sheet is obtained by forcing a thicker sheet through a set of rollers rotating in opposite directions.

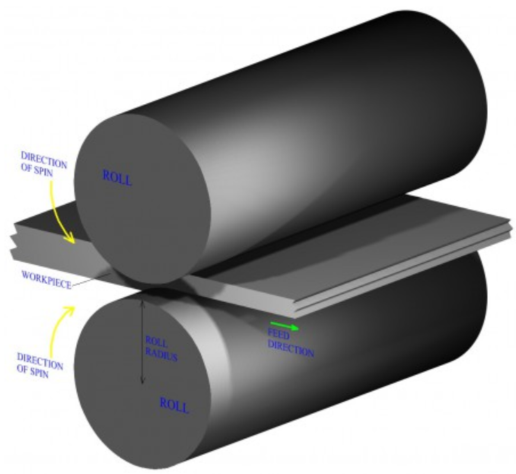

Figure 1.8: Sheet rolling [34]

Another process which could be considered is roll forming, in which the metal sheet is progressively passed through a number of rollers which gradually modify its shape towards the desired end result. Such a process can be seen in Figure 1.9 [39].

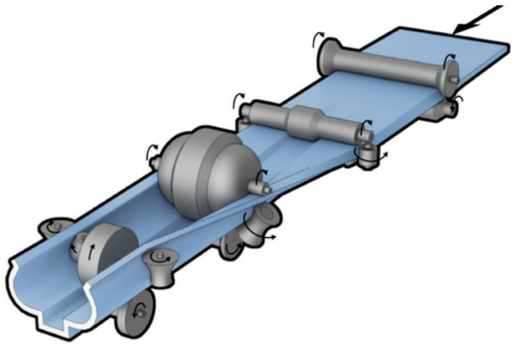

Figure 1.9: Roll forming [39]

Lastly, for metal part manufacturing, a few more processes were looked into during the literature study, including casting, forging, extrusion, laser and water jet cutting, however due to the manufacturing techniques that are more often used in the industry for manufacturing wing ribs, it was decided that they are not relevant anymore, and therefore they will not be presented in detail within this review.

As previously stated, when a part is manufactured using machining processes, it is possible to obtain the final shape straight away, as opposed to bending processes. For these, methods for bringing all constituent parts together into the substructure have to be considered. As the metals at hand are aluminium alloys, not many options are available. The first one and most likely to be used is mechanical fastening, using rivets and nuts and bolts. This is a standard procedure for many structures and it is generally applicable to these alloys as well. Other options included welding and adhesive bonding, however the selected alloys have poor weldability [3], and adhesive bonding is more suitable for composites. In addition, adhesive bonding requires intensive surface preparation such as surface abrasion and degreasing, which not only make the process more complex, but also increase the amount of chemical waste generated.

Moving onto the composite part manufacturing, the same approach as for aluminium was taken. During the literature study [47], a number of different processes were looked into, however only the most relevant ones based on industry practice were selected for this report. The first aspect which was looked into for composites was the method for ply layup, with the alternatives being hand layup and automated lay-up (via automated fibre placement (AFP), automated tape laying (ATL), or filament winding). Hand layup is considered the oldest and simplest technique [38], but it has however undergone a series of changes over the years. The old processing method started with the mould being covered with a release agent, followed by a thin sheet ensuring a smooth surface finish. The carbon fibre fabrics were then cut in the correct shapes and sizes and placed on the mould. Lastly, the resin was added to them, typically with the use of a roller. The part was then covered with another peel ply, release film and a breather so that excess resin could be removed during curing and also to ensure air flow. A newer approach to this process however uses pre-impregnated fibres (prepregs) directly. These prepregs come on rolls and they are manually added onto the mould. The next step is bagging, followed by curing. As a result of the fibres being impregnated with the exact amount of resin required (roughly 40% volume), no resin needs to be removed during the curing stage **[Marc Koetsier, personal communication, 26.08.2022]**. In such a process, waste is generated as a result of the separation foils required on each side of the prepregs (since epoxy is tacky before the layup): the bags used for vacuum bagging, and the other consumables such as the sealant tape and the breathers.

Filament winding was removed from the list of processes for the wing rib since it is more suitable for parts that are cylindrical or with closed cross-section. For the automated processes however, there are still two options which were considered. These are automatic fibre placement and tape laying. These two processes have a similar working principle [15]. Tape laying is a process which is usually required for larger, flat parts since a larger material deposition is possible. Fibre placement on the other hand is more suitable for parts that have complex shapes (e.g. with larger curvatures) [29]. The fibres or tapes are placed on the mould by a roller, typically mounted on a robotic arm with various degrees of articulation. The roller applies pressure and in some cases also some heat (especially for thermoplastic tapes).

The next types of processes looked into were liquid moulding processes, where resin is infused into fibres after their placement in the mould. These processes are very varied, however one that is used in the industry is resin transfer moulding (RTM). In this process, dry fibres are placed in the mould, following the orientation and stacking sequence provided in the design of the composite. The first mould used in such a process is for the preform generation. The mould is closed over the fibres and pressure is applied in order to give them the rough shape of the final part. The preform is then removed and added in a separate mould, where the infusion process will take place [29]. Once in the mould, the resin is infused through a system of tubing set up depending on the geometry and resin infusion speed required. These infusion processes are generally responsible for a large amount of waste generated during production. Some waste products resulting from them include left-over resin (since a margin is taken above the calculated required one in order to prevent running out mid-infusion), any plies and foils, seals and tubing used in the process. Another note which will be added here, is that these processes are applicable to thermosets, since thermoplastic resins have high viscosities, which would be troublesome for infusion.

For thermoplastic materials, processes such as press forming and thermofolding can be used. These involve heating up the material, either in its entirety (press forming), or only locally (thermofolding) and then applying pressure with a press in order to give the material the end shape. These processes can be used to preform the thermoplastic material after layup. The next step is to place the preform in a consolidation press, where it is heated and kept under pressure in order to obtain the final part. One additional process which will be considered since it could be used both for thermosets and thermoplastics is the use of an autoclave. This places the composite at high temperatures and pressures for a given amount of time, resulting in the final part. Some bagging processes are required for this however, which increases not only the energy consumption (due to the autoclave functioning temperatures), but also the waste generated.

Similarly to aluminium, some components may require assembly even in the case of composites. This time however, mechanical fastening is difficult to achieve due to the possibility of the composites delaminating during drilling, and also during rivet expansion during assembly, which could cause cracks and further damage at the edges of the hole in which it is placed. Nuts and bolts are however still an option considering the holes can be drilled with care. Processes which could be used instead are secondary bonding, co-bonding and co-curing, as well as welding (for thermoplastics only). In secondary bonding, two composite parts are put together using an adhesive. The disadvantage for these parts however comes from the certification side [12]. Co-bonding on the other side takes a part which is already cured/consolidated, and one which is uncured. Adhesives are added between the two and the second part together with the adhesive are allowed to cure, thus bonding to the originally cured single part. Lastly, co-curing involves two parts which are uncured/unconsolidated. The parts are placed together in the autoclave or press and left to cure/consolidate. This is strictly speaking not considered a bonding process however since the parts are both uncured/unconsolidated at the beginning of the process [12]. An exemplification of the three processes can be seen in Figure 1.10.

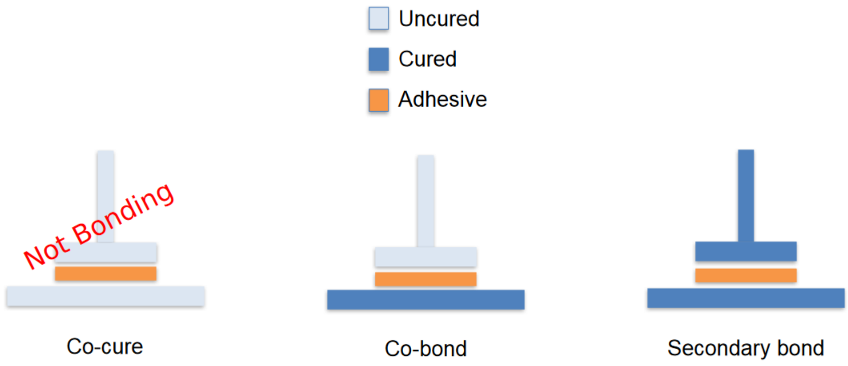

Figure 1.10: Co-curing (co-consolidation), co-bonding and secondary bonding of composites [12]

Lastly, thermal welding is a process which can be applied to thermoplastic materials due to their ability to melt without being damaged. Some of the welding techniques that could be used are ultrasonic welding, induction welding (more commonly used in aerospace structural applications), resistance welding and laser welding. Specifically, ultrasonic welding was looked into more detail only due to it being used in some of the processes which will be considered in the case study of the wing rib, although its use is mostly limited at the moment to attachments rather than structural applications. The process itself relies on high frequency vibrations which heat up the material locally due to the friction force created at the point of contact. In order to direct the heat at the desired location, energy directors will be used, which are resin protrusions at the weld line, made from the same type of resin as that used in the composite parts. These energy directors melt, becoming part of the weld line at the end of the process [12]. An example of such energy directors can be seen in Figure 1.11 [7].

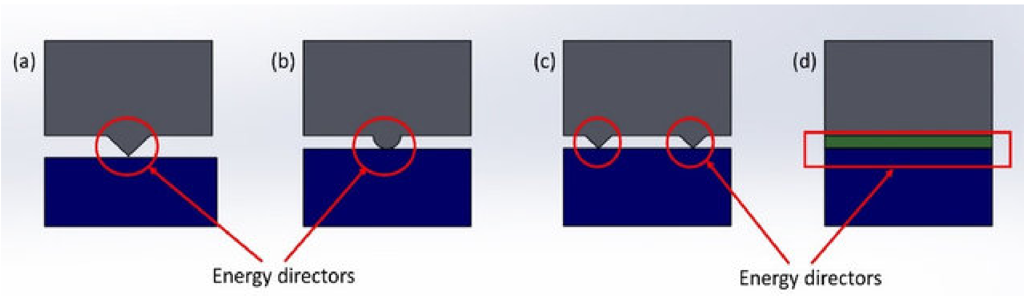

Figure 1.11: Different shapes of energy directors [7]

1.3.4. Life cycle assessment (LCA) and value stream mapping (VSM)

In order to be able to assess the environmental sustainability of the different materials and their processing methods, a tool had to be selected. Two methods identified were the life cycle assessment and value stream mapping. While LCA is a tool which was specifically developed due to the constantly increasing demand for sustainable technology [11], VSM is a tool which is used within the lean manufacturing ideology, with the main objective being to identify waste and reduce/remove it. As discussed previously for sustainability, due to the three main pillars considered, in some sense, VSM automatically achieves a certain level of sustainability for the simple fact that reducing waste in itself reduces the impact that a product will have, regardless of the nature of waste considered (actual physical waste, time, money, energy, etc.). Additionally, the tool could also be used to make an inventory of energy consumption and costs of different processes. The final choice was to use LCA as the main analysis tool. However, since material flows have to be determined and stream mapping is required to some extent in the flowchart drawing stage of the process, certain elements of VSM will be visible also. Sustainability is a complex area of study, which involves multiple stages of a component's life, in other words what is referred to as cradle-to-grave when components are discarded at the end of life, or in the case of recyclable parts cradle-to-cradle. Here, recycling refers to the reprocessing of the material from which a component was made and reusing it in new components. Typically, recycling would imply the reprocessing of the material into similar quality material that can be used for a similar structure as before (e.g., from a primary structure back to another primary structure). If the original material is reprocessed into a lower quality material, this is generally referred to as downcycling (e.g., from a primary structure to a secondary structure or non-structural part). One way to ensure that this assessment of the different life stages is done consistently by all LCA users worldwide, is to generate standards. ISO standards from the 14000 series are the ones concerned with environmental management, and specifically 14040 [27] and 14044 [28] for LCA practitioners. As a main rule, an LCA is typically divided into four stages [11][27], namely the goal and scope definition, inventory analysis, impact assessment and interpretation and evaluation of results. The goal and scope definition stage aims to define the depth required for the analysis, including the elements which are or are not relevant. The first step is to select a functional unit, which is the subject of the study. This functional unit must define the product and its function. For the case at hand, an example of functional unit would be a wing rib capable of carrying the required operational loading for an Airbus A320 type aircraft. The next step is to define the boundaries of the system. A cradle-to-grave system looks at the parts from the raw material stage, all the way until the end of life disposal of the part. A cradle-to-cradle, looks at the progress from raw materials back to raw materials. Additional boundaries could also be cradle-to-gate which looks at the processes from raw materials until the start of the part manufacturing processes, or gate-to-gate which looks only at the manufacturing processes [49]. During this goal and scope phase of an LCA, a large number of assumptions may be made, and it is important that these are appropriately documented such that the results of the LCA are verifiable and reproducible. For the purpose of this report, any assumption will be clearly highlighted as seen in the following blue box.

Assumption

This is an assumption box.

Moreover, the assumptions will also be gathered in Appendix A for convenience purposes.
The second stage of the LCA is the inventory analysis. During this stage, the data regarding the processes involved in the part production is gathered (as well as for any other processes included within the system boundary). This data can be divided into data that is collected locally/recorded in real time during the process (primary data), or it can be collected from databases and other resources (secondary data)[49]. Once all the data is collected, the impact assessment can be conducted. Here, the different inputs and outputs are typically mapped out and their potential effect on the environment is analysed. In the case of this project this could for example be done by looking at the GWP due to the emissions. Lastly, the LCA is concluded with an interpretation and evaluation stage, where the procedure is checked, the numbers are verified, and preferably a sensitivity analysis is conducted. Additional steps such as peer reviews may also be required at this stage if the results of the assessment are meant to be used for marketing purposes or promotion of a product [49].

Among the advantages that are immediately noticeable for an LCA one can mention the ability to determine the impact that each individual stage of life has on the environment and as a result also to effectively identify areas of improvement (and prioritise them based on the results). Another important advantage is given by the ability to compare two different products. This allows one to make an informed choice in designing of new components. There are of course also disadvantages to performing such an assessment. According to ISO14040 [27], an LCA will most of the times not consider every issue concerning a certain system, since by standard procedure, one will limit the analysis to the initially defined goal and scope, which are specifically designed to narrow down the study. Therefore, as expected, this indicates the importance of the first step of setting up an LCA, since all the assumptions made and simplifications applied may significantly change the results. Another important limitation can appear in the inventory analysis phase. ISO 14040 once again mentions that despite the general indications on how to perform an LCA, there is no set way in which the LCI (life cycle inventory assessment) must be conducted, and which data is and is not considered. Once again this choice is at the discretion of the person conducting the LCA. The freedom present in the two stages mentioned above, of choosing the data and making assumptions of course can result in problems if the integrity of the study is not checked. For instance, data can be manipulated and excluded in order for the results to look better [49], which justifies the need for a peer review when the results are used for marketing purposes for instance, where the reputations of the manufacturer and competitors are at stake. Another limitation of such a method comes from the difficulty of acquiring data for the LCI in the first place. This process is very time consuming and in some instances the data obtained is hard to verify. This can happen with information such as energy usages and waste since they are the results of process parameters and therefore can sometimes be kept confidential by the manufacturers. This not only increases the difficulty of finding such data, but also makes its reliability questionable since it is not always verifiable [4]. Lastly, some data such as CO_2-eq emissions are not directly measurable as mentioned in previous sections, and the calculations involve coefficients coming from the energy mix of a country and conversion factors. These are numbers which are changing based on the developments happening in the said countries, and also based on for example the amount of green energy that can be used in a certain period. Therefore, the data collected or estimated at a certain date may not be the same as data collected in subsequent studies.

1.3.5. Case study: Wing of Tomorrow Program

This is a short subsection introducing the Wing of Tomorrow (WoT) program started by Airbus, since the rib which is to be analysed in this study is a part of this project. Many attempts are made to improve the efficiency of aircraft by looking either at new materials, different fuels, different aircraft design, etc. In some situations, these attempts must be combined in order to obtain a good result. Taking as an example electric aircraft, one of the challenges faced with structural designs would be caused by the weight of the batteries, compared to the fuel used nowadays, and specifically their weight which remains constant during flight, compared to fuel which burns rendering the aircraft lighter. Such an increase in weight would require partial compensation (considering only the weight of the burnt fuel) from other areas, such as the wing structural weight. By designing components from composites, this could provide a solution. The goal of Wing of Tomorrow is therefore to focus on newer, improved methods of manufacturing and assembly of wings, including of course the use of composite materials, but also on aspects such as aerodynamic design [54].

1.4. Thesis objectives

With the literature study reviewed, this section aims to give the main objectives of this thesis, or in other words how the information gathered is going to be used.

As it was mentioned before, there are a large number of materials and processes that are available for the manufacturing of aerospace parts. Based on discussions within GKN Fokker, it was decided that a certain number of manufacturing routes will be investigated for both aluminium alloys and composites. First of all, as presented previously, the aluminium alloys chosen are Al7075 T73 and Al7050 T7451. The composites chosen are a thermoset Epoxy CFRP, and a PEKK CFRP for the thermoplastic alternative. The main processing routes chosen for aluminium are machining and and sheet forming, with one rib being considered for each manufacturing route. For the composites, an RTM infusion option and a prepreg one will be considered for the thermoset rib, while for the thermoplastic rib only preforming followed by out of autoclave consolidation will be looked at.

The main objective is to conduct a study on the energy requirement and CO_2-eq emissions in a general manner, such that the numbers could be applied to a certain part that must be manufactured. This will be done by looking at the different stages of life of a part: raw material production, manufacturing, operational phase and finally end of life. Some additional steps which will be considered as well are the transportation of the parts to the manufacturing lines.

Once this general study is conducted for all the materials and processing options selected, an LCA will be performed using the numbers obtained and applying them to a specific part: wing rib number 14 within the Wing of Tomorrow project run by Airbus. The end goal of this analysis is to be able to provide a first comparison between the different materials and their corresponding manufacturing routes from an environmental sustainability perspective. This study is meant to provide insight into the sustainability of the manufacturing processes chosen for the rib within the Wing of Tomorrow project, and pave the way for further detailed research into each individual stage of the parts' life cycle such that the most sustainable alternatives are chosen for the future.

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2

Material Flow Charts and Data Collection

With the background information presented, the next step before being able to analyse the environmental sustainability of the wing rib, is to investigate the sustainability of the different materials by looking at general data concerning their primary production, manufacturing, operational life and lastly the end of life stage. By general data, it is meant that the numbers could be taken from this section for any part made out of the materials selected and choice of processing steps, and they can be applied to said part based on its geometry and general specifications in order to estimate its environmental sustainability. This section commences with the material flow charts created for the different materials, and continues with the data collection process itself, further divided into subsections for each material.

2.1. Material flow charts

In order to be able to search for data in an organised way, the first step was to draw process flow charts for each of the materials considered and also for the different processing routes that could be taken. The results can be seen in Figure 2.2, Figure 2.3 and Figure 2.4. As mentioned in the earlier sections, waste is not the main concern of this study, however it will be mentioned at relevant processing stages. This was taken into account already from the flow charts. Each processing step which has certain byproducts (whether recyclable or just waste), is marked with one or a set of coloured circles. As seen in the legend of the charts as well, a green circle represents outputs which are recyclable (e.g. aluminium chips) while a red circle indicates a non-recyclable waste or any other wastes such as consumables or composite materials (e.g. excess resin, fibres, bagging materials).

Starting with the metals, a quick summary of the exact outputs will be given. As it can be seen, in the case of both sheet metal processing and machining, most of the stages involved in the aluminium flow charts are accompanied by green marks. This is because processes such as machining, cutting and trimming produce either aluminium chips or larger aluminium pieces which are recyclable as it will be addressed later on in the data analysis section. The assembly stage of the sheet metal processes is also given a green mark due to the possibility of having excess rivets/damaged ones that are also made out of aluminium and therefore also recyclable at their turn. A red mark is also given here however since in the case of adhesive bonding, there could also be non-recyclable waste produced such as excess adhesives. Lastly, the surface preparation and painting stages in both processing routes are given red marks due to the excess paint and primers that will result from the processes and that go to waste.

In the case of thermoset composites, all of the process steps are given red marks due to the low recyclability of the materials. This will once again be addressed in more detail in the data collection section. Additionally, compared to aluminium, composites also have a waste indicator in the storage phase. This was predominantly added due to the amount of composites which go to waste due to them exceeding their shelf life and never making it into production, as can be seen in Figure 2.1.

Any layup and bagging processes are also given a red mark due to the large amount of plastic bags and sealants and tapes that are required and which are only used once. In some cases, alternatives exist such as silicone moulds to replace the plastic bags, however since the standard practice is still the use of bags, it was considered appropriate to keep it as such for this report too. Nevertheless, it should also be noted that even silicon vacuum bags have a set number of cycles after which they require

Figure 2.1: Composite material waste. Photo credits: GKN Fokker

replacement as well. Lastly, the infusion processes also require a large number of consumables such as tubing, seals and tapes, and on top of these, excess resin is also typically expected (both left over in the tubes, and in the starting recipient since it is preferred to have excess resin to throw away than run out of resin mid-infusion which would result in the entire part being scrapped).

For the thermoplastic materials, most of the steps are marked with both a green and a red mark due to the thermoplastic resin being recyclable, while the carbon fibres are generally speaking not. If the two could be separated (can not be done in practice), that would result partly in material that can be recycled (thus the green mark) but also fibres which are waste or that could be combusted for energy (thus the red mark). In practice, the recycling of thermoplastic materials has progressed significantly, with attempts at recycling entire composite structures having been completed at GKN Fokker. For this, the material containing both the fibres and the resin has been shredded and then reused to generate new structures. This process is discussed further in paragraphs on the end of life of thermoplastic PEKK-CFRP out-of-autoclave consolidated composites.

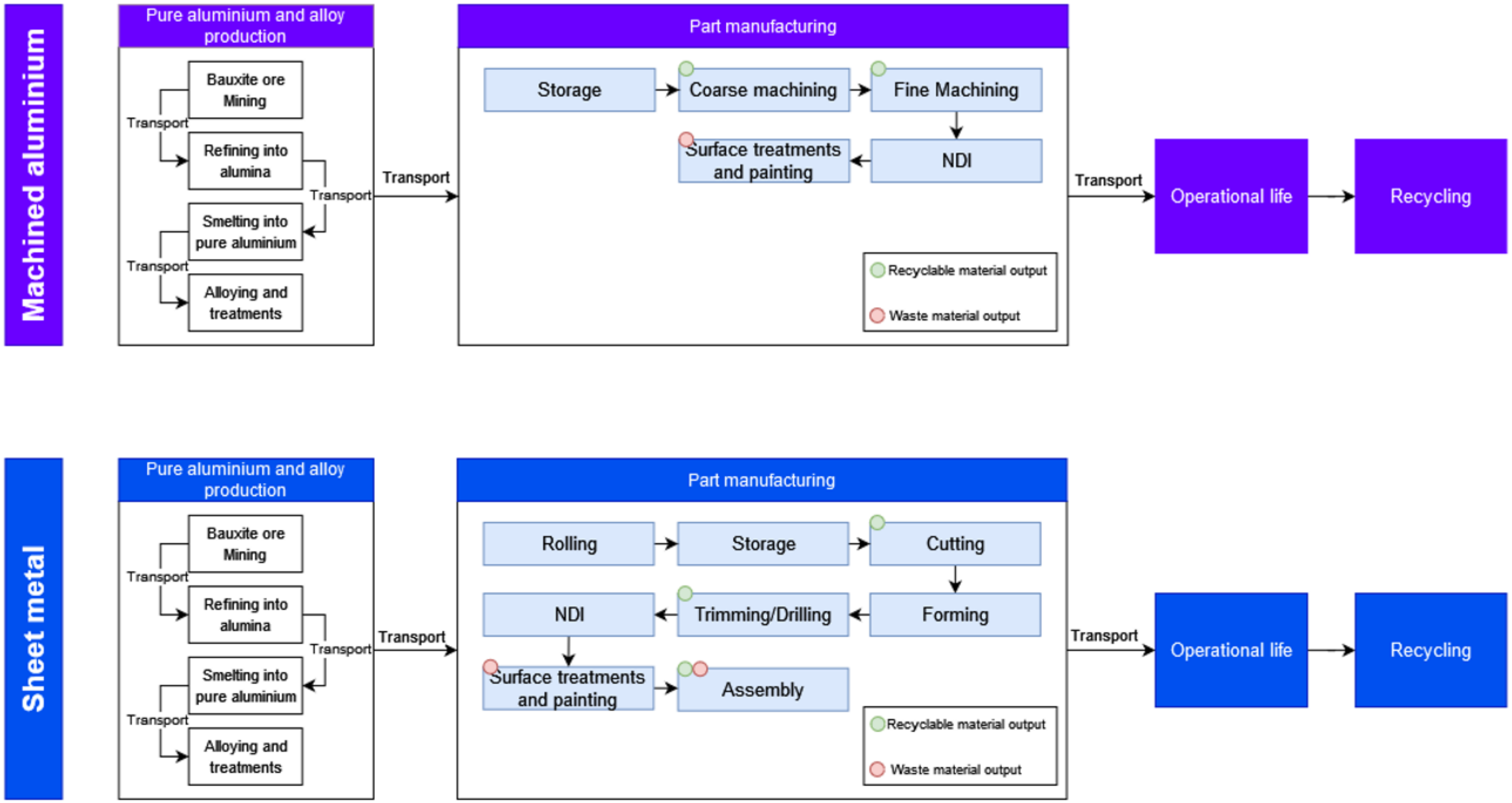

Figure 2.2: Aluminium processing flow charts

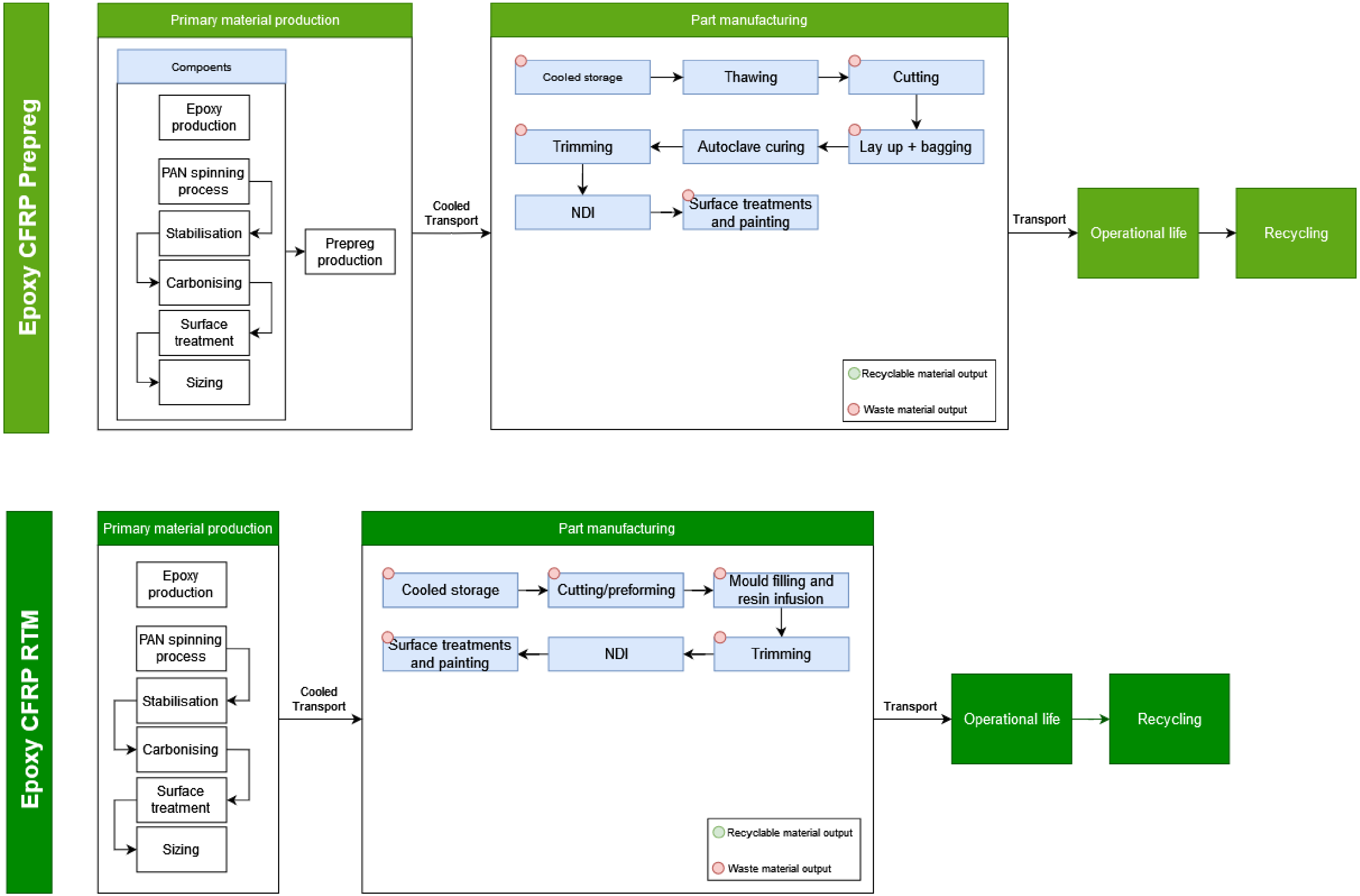

Figure 2.3: Thermoset processing flow charts

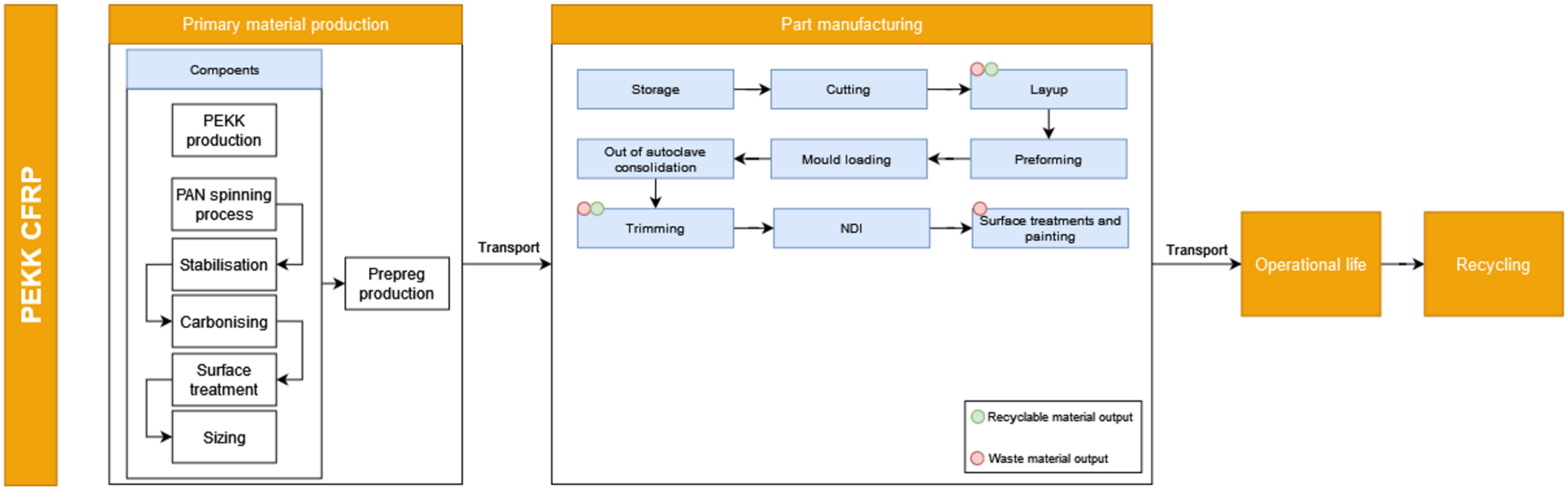

Figure 2.4: Thermoplastic processic flow chart

2.2. Data collection

This section is concerned with the data collection for the LCA. This could be considered a first step in the LCI, with the main difference being that the numbers will be kept general such that they could be applied to any other part later on. In future sections, the data will be applied to the wing rib and that will be considered the official LCI for the project. Each subsection of this section is concerned with one particular material and its manufacturing flow. Data for this chapter was collected from databases such as that of EduPack [3], as well as other sources such as articles, websites and primary data obtained from GKN Fokker. When numbers are presented, the data comes predominantly from EduPack, unless otherwise stated.

2.2.1. Machined aluminium

The data for all materials was divided based on the different stages of a part's life, and they will be presented in this way for all subsections.

Raw material production

The first stage that had to be considered was the raw material production. As described in the background information section, aluminium is obtained from bauxite which has to be refined into alumina and then smelted into pure aluminium. This is then mixed with other elements and the engineering alloys are obtained. Individual energy consumptions at each stage were difficult to find. In this case, software such as CES EduPack were used, where the entire process of obtaining specific aluminium alloys was bundled into one data point. This energy was referred to as embodied energy for primary production, and was defined as ”Energy required to make 1 kg of the material from its ores or feedstocks” [3]. The sources of these numbers are LCA databases such as those of EcoInvent and other literature such as the Inventory of Carbon and Energy [24] or reports by PlasticsEurope [17]. An aspect that one may notice when searching for numbers in such databases is that they are always given as ranges. This lead to one of the first assumptions, that the number which has to be used is the largest one given in the range. The reasoning behind this was to ensure a conservative study since it is a preliminary one. In other words, the worst case scenario is considered for all processes and materials under investigation, since it is assumed that any changes will result in improvements at company level.

Assumption
When ranges are provided for data sets, the most conservative values should be taken for the calculations to ensure a conservative result.

For machined aluminium, it was previously established that two alloys will be used, Al7075 T73 and Al7050 T7451. For these two, the embodied energies found were of 203 MJ/kg and 201 MJ/kg respectively. In addition to these, the CO_2-eq emissions were also found as 13.8 kg/kg and 13.7 kg/kg respectively. Dividing these by the energy, one can see what conversion factor was used, and in this case for both alloys, this is roughly 0.068 kg CO_2-eq per MJ. Checking the country electricity mix[1], one can see that the CO_2 footprint conversion factor varies, and therefore, at this stage in the study it will already be required to apply some of the information on materials used within GKN Fokker.

The aluminium used is brought to the factory predominantly from France (around 80% of the time), and on rarer occasions from Canada **[Jos Thoolen, personal communication, 13.06.2022]**. Moreover, since the electricity mix varies over the years and the databases at hand are not the latest versions, a collective decision was made with the GKN supervisor to use the conversion factor given for Europe rather than just the one of individual countries (in this particular case France). The conversion factor that will be used is therefore 0.113 kg/MJ.

[1] `http://support.grantadesign.com/resources/cesedupack/2019/help/html/eco/ecodata_countryelectricitymix.htm`

> **Assumption**
>
> *When process energy is involved and the country energy mix is required, the CO_2 footprint conversion factor used will be for the whole region rather than the individual country (e.g. Europe instead of France, or North America instead of Canada).*

Using this factor and the energy requirement for the processes, the CO_2-eq for Al7075 T73 and Al7050 T7451 are calculated at 22.94 kg/kg and 22.71 kg/kg respectively.

Transport
For the transport of material, a number of different options were investigated. These were road transport (via a 40 tonne, 6 axle lorry)[3] and air transport (short and long haul). For the road transport, an energy requirement of 0.94 MJ/tonne/km was found, while for the air transport 12 MJ/tonne/km were required for short haul flights and 6.5 MJ/tonne/km for long haul flights [3]. All of the means of transportation present in the database were presented with a CO_2 footprint conversion factor of 0.072 kg/MJ. As opposed to the previous case where the energy mix of the countries was considered, the CO_2 footprint is now predominantly given by the fuel used, and therefore this value will now be used as found in the database.

> **Assumption**
>
> *When transport energy is concerned, the CO_2 footprint conversion factor used is 0.072 as provided in the database of CES EduPack for transport energy.*

Part manufacturing
The part manufacturing starts with the storage of the materials into warehouses or deposits until they are used in production. In the case of aluminium, since it does not have any storage temperature requirements, the energy consumption at this stage is minimal. The only conditions are that the room is kept dry and that the aluminium is sheltered from coming in contact with water or other liquids to prevent corrosion. As a result this was kept as negligible, both for energy consumption and CO_2-eq emissions.

When the part needs to be made, the aluminium blocks are taken into the machining area. Here, two types of machining are available. The first is coarse machining, where large amounts of material are removed. For Al7075 T73, this process has a reported energy consumption of 1.96 MJ/kg of material removed. Using the energy mix again, the CO_2-eq emissions can be calculated at 0.22 kg/kg of material removed. For Al7050 T7451 on the other hand, slightly larger values are found, of 2.12 MJ/kg of material removed and an equivalent CO_2-eq emission of 0.24 kg/kg of material removed. The next step after coarse machining is fine machining. This process is required for adding the details to the part, and therefore it is more energy intensive than the previous one. For Al7075 T73 the reported value is at 14.80 MJ/kg of material removed, resulting in approximately 1.67 kg CO_2-eq per kg of material removed. Alternatively, for Al705 T7451, 16.50 MJ and 1.19 kg/kg are obtained.

Once the machining is done, the part needs to undergo testing in order to ensure that the quality is sufficient. This is done using NDI (non destructive inspection), and specifically with die penetrant inspection. This process can be divided into a preparation stage and the inspection stage. The preparation stage involves taking the metal part and degreasing it, followed by pre-penetrant etching where a thin layer is removed from each face of the part using acid **[Patrick Minke, personal communication, 04.07.2022]**. For this entire process, data from GKN Fokker was used, with a maximum power consumption of 216 kW, most of which comes from the power required to heat up components for the degreasing stages (up to 65°C). Collectively, these would add up to a time of roughly 15 minutes (0.25 h). The energy can then be calculated as 54 kWh, equivalent to 194 MJ. This of course is the energy used for multiple parts simultaneously, since the baths that are used can take up more than just one component. The CO_2-eq generated in this case is of 21.92 kg, and once again it is divided among the parts which go in the process simultaneously. The values remains the same for both types of alloys as the process does not differentiate between the two. After the part is ready, during the penetrant inspection it is lowered into fluorescent die, then dried in an oven, after which it is rinsed and inspected using an UV lamp. Any cracks/imperfections will retain the die penetrant and will show under UV. In this part of the process, the most energy intensive one is the oven drying since heating processes generally use a lot of energy. In this situation, the exact properties of the furnace used were not found, and therefore some assumptions and calculations had to be performed. Firstly, the oven input specifications were of 380 V and 30 A. The first assumption here was that an oven with a capacity of 1 m^3 will be used. Considering that the air has a density of 1.225 kg/m^3 at sea level, a specific heat capacity of air of 0.718 kJ/(kg·K) [2], that the room temperature will be at around 20°C and the drying temperature is of around 50°C **[Paul Boon, personal communication, 05.07.2022]**, the energy required to heat up the air can be calculated as seen in Equation 2.1.

$$Q = m \cdot c \cdot \Delta T \tag{2.1}$$

where Q is the heat energy, m is the mass of the air being heated up, c is the specific heat capacity of the air, and ΔT is the change in temperature expected. This calculation results in 26.39 kJ of energy. This however is only a small portion of the energy required in a furnace. Typically, such furnaces will have refractory materials such as refractory bricks on the inside to contain the high heat and reduce heat energy leaks. These will also require a large amount of energy to heat up to the 50°C needed for the process. In the absence of data about the actual furnace present at GKN Fokker, some arbitrary refractory bricks were chosen from retailers online. This was the Helios R 65SA 230x114x64 mm brick[3]. Using the certificate of conformity of the bricks, provided by the manufacturer [41] a brick density of 2000 kg/m^3 was found, and additional research into refractory bricks found that the specific heat capacity of such materials is from 0.7 to 1.2 kJ/(kg·K)[40]. As per the previous assumptions made, when ranges are given, the worst case scenario shall be considered, and as such a specific heat capacity of 1.2 kJ/(kg·K) was decided upon.

First, the number of bricks that would be required to cover the walls of the 1 m^3 furnace had to be calculated. The surface area is of 6 m^2, and this has to be divided by the surface area of the face of one brick (based on sizes given above, of 0.0226 m^2). This results in about 228.83 bricks, which was rounded up to 230 for ease in calculations. One aspect that has to be kept in mind is that the overlaps that would occur due to the geometry of the bricks covering the walls of the furnace were ignored. This was considered appropriate since the calculation is an estimation, and moreover considering more material will actually result in a conservative calculation which is the aim of this study to begin with. The volume of the bricks can also be calculated by multiplying their surface area area by their thickness, and the result is of 0.00167 m^3 per brick. This, together with the density mentioned before can be used now to find the mass of the bricks, and following this, Equation 2.1 can be used again the same way as for the air in order to estimate the heat energy required to bring the refractory bricks to the required temperature of 50°C. This calculation results in 27.7 MJ of energy, which makes the energy required for heating the air negligible in comparison.

$$\begin{aligned} Q &= (0.00167 \cdot 2000 \cdot 230) \cdot 1.2 \cdot (50 - 20) \\ &= 27655.2kJ \end{aligned} \tag{2.2}$$

Using a conversion of 1 kWh = 3600 MJ. As can be seen here, the amount of energy required for the heating of the bricks is really large, and therefore the energy that would be added for heating also a part that goes in the furnace will be negligible in comparison.

The energy is however very large if only one part goes in the furnace at a time. This becomes more manageable if multiple items can go in simultaneously, similarly to what was mentioned for the preparation phase of the process. If this happens however, the previous assumption regarding the energy for heating the parts is not valid anymore. A check can be performed here for this. Let us assume an aluminium wing rib, with an approximate weight of 3.66 kg, made out of Al7075 T73 (specific heat capacity c = 0.95 kJ/(kg· K) [3]), and a capacity of 30 ribs in the oven. Considering the change in temperature will also be of 30 K as in the previous calculation, the heat required to raise the temperature of the 30 wing ribs can be calculated at roughly 3.1 MJ. This brings the total energy consumption for this process at 30.8 MJ. Lastly the CO_2-eq value in this process comes out at 3.48 kg.

[2]https://whatsinsight.org/specific-heat-of-air/
[3]https://www.hornbach.ro/p/caramida-refractara-helios-r-65sa-230x114x64-mm/8190823/

Assumptions

- *The oven for drying the parts during NDI steps has a capacity of 1 m*^{3}.
- *Air density at sea level is 1.225 kg/m*^{3}.
- *Specific heat capacity of air at constant volume is 0.718 kJ/(kg·K)*.
- *Room temperature of 20°C*.
- *Furnace used at full power for heating stage*.
- *The refractory bricks used are Helios R 65SA 230x114x64 mm*.
- *Specific heat capacity of refractory bricks is 1.2 kJ/(kg·K)*.

The next step after NDI is the anodising of the parts. Anodising is required in order to increase the thickness of the oxide layer that is found at the surface of the part, thus increasing its corrosion resistance. It is a process that is suitable for aluminium parts, but also for other non-ferrous metals such as titanium or magnesium [52]. This process is an electrochemical one, and therefore relatively costly for the environmental sustainability, mostly due to the high amounts of electricity required both for the oxidation process and for maintaining the electrolyte temperature during it [16]. A standard practice for anodising processes involves the use of hexavalent chromium, and is known as chromic acid anodising. This compound however is toxic and carcinogenic, and therefore is slowly removed from the industry whenever possible, and replaced with other processes such as sulphuric-tartaric ones (TSA) [10]. This process has become a standard in the aerospace industry in Europe [16] and therefore is the one considered for this thesis, especially considering the project Wing of Tomorrow, which will be conducted using sustainable processes. For such anodising processes, the energy requirement is reported at roughly 0.4 kWh/m^2 [16] or 1.44 MJ/m^2. The same source states as well, that there is a large variety of settings for these processes however and therefore it is difficult to estimate the optimum ranges of parameters, both for increasing the corrosion resistance of the material but also for having an energy efficient/saving process. Considering the estimated energy value given above, the CO_2-eq emissions can be calculated using a conversion factor of 0.113 kg/MJ again based on the electricity mix, resulting in a value of 0.163 kg/m^2.

After anodising, the last step is to paint the parts. This is done first by applying a layer of primer which covers the part improving paint adhesion later on, while simultaneously ensuring that the paint is not absorbed by the material thus requiring additional layers. Painting is done using pneumatic paint guns, and therefore the energy usage comes from a compressor. As a result, the exact energy requirement is difficult to estimate. This is due to the fact that compressors at company levels will be very large and will be used to power up all pneumatic devices in the factory. Moreover, once the paint is applied, the parts are required to go through a drying phase in a furnace once again. As seen in previous steps, these heating processes require a large amount of energy which makes the surrounding processes negligible in comparison. As a result, it was assumed for the time being that the paint guns themselves use a negligible amount of energy.

Assumption

Paint guns use a negligible amount of energy.

The gas furnace used at GKN Fokker is reported to have a power of 26 kW, and a constant air flow. As a result it is considered that it is working constantly during the drying phases. It was also reported that the time required to dry the parts is of 1 hour and 15 minutes for all the layers combined. Multiplying the power by the running time results in an energy of 32.5 kWh, or equivalently, 117 MJ. This will of course be once again distributed among all the parts that are placed in the furnace to dry simultaneously. The CO_2-eq emissions are calculated at 13.22 kg for this energy consumption.

Operational life

For the calculation of the impact of the operational life, it was required to see how much energy is used for transporting a certain weight over a given distance. One way to do this in the case of aircraft is by considering their lift to drag ratios (L/D). The lift to drag ratio is also referred to as the glide slope of an aircraft. If one were to assume that the engines are suddenly switched off during flight, the energy loss would be calculated as follows [1]:

$$E_{loss}\text{ (per kg·km)} = \frac{m \cdot g \cdot H}{m \cdot d} = \frac{g \cdot H}{d} = \frac{g}{\frac{L}{D} ratio} \tag{2.3}$$

where m is the mass of the flying object, g is the gravitational acceleration, H is the altitude and d is the distance travelled. This is the energy that the engines would theoretically have to supply in order to prevent the aircraft from losing altitude, in an ideal situation where the fuel efficiency would be 100%. In reality, this is not the case. The average energy efficiency of a modern aircraft engine is at roughly 35% [46]. As a result, the energy calculated in Equation 2.3 has to be divided by this efficiency in order to see the actual energy input required. Knowing that the project is looking at the Wing of Tomorrow which will be applied on an aircraft similar to the Airbus A320, the L/D ration for the A320 was found at 16.3 [33]. Substituting the values provided above in Equation 2.3, a value of 0.6016 kJ/(kg·km) can be obtained, and by further division by the engine efficiency, 1.72 kJ/(kg·km). The unit conversion from m/s^2 to kJ/(kg·km) and the additional version using MJ and tonnes for potential future calculations can be seen below:

$$\frac{m}{s^2} = \frac{J}{kg \cdot m} \tag{2.4}$$

$$= \frac{kJ}{kg \cdot km} \tag{2.5}$$

$$= \frac{MJ}{tonne \cdot km} \tag{2.6}$$

Please note that here, the CO_2-eq will be calculated once again using the 0.072 kg/MJ conversion factor due to the fact that the energy is obtained from fuel burning rather than the electricity grid as it was the case in the processing steps. The total calculated amount comes at $0.124 \cdot 10^{-3}$ kg/(kg·km).

End of life

At the end of life, there are a number of actions which can be taken with regards to a part. In the case of metals, they could be recycled, downcycled or deposited in landfill sites. These are mentioned here in increasing order of environmental burden. Considering that aluminium has been reused in proportions of up to 75% since its first use [8], it was assumed that for the scope of this paper, all recycled aluminium is taken back into same quality aluminium, therefore no downcycling takes place. Energy data for recycling of aluminium was taken once again from the CES EduPack database, as 34.9 MJ/kg for Al7075 T73, and 34.6 MJ/kg for Al7050 T7451. The equivalent CO_2 emissions are therefore 3.94 kg/kg and 3.91 kg/kg.

Assumption
All aluminium components are recycled into same quality aluminium material.

Summary
All of the data discussed in the previous paragraphs can now be summarised in two tables, one for each aluminium alloy considered.

Table 2.1: Summary machined aluminium - Al7075 T73

Stage	**Small ribs (thickness < 100mm) Al 7075 T73**			
	Energy	**Unit**	**CO_2-eq**	**Unit**
Raw material production	203	MJ/kg	22.94	kg/kg
Transport:				
- Road	0.94	MJ/(tonne·km)	0.072	kg/MJ
- Air (Short haul)	12	MJ/(tonne·km)	0.072	kg/MJ
- Air (Long haul)	6.5	MJ/(tonne·km)	0.072	kg/MJ
Part Manufacturing:				
- Storage	Negligible	-	Negligible	-
- Machining (coarse)	1.96	MJ/kg removed	0.221	kg/kg removed
- Machining (fine)	14.8	MJ/kg removed	1.672	kg/kg removed
- NDI (die penetrant)				
> Preparation	194	MJ/batch	21.922	kg/batch
> Oven	30.8	MJ/batch	3.48	kg/batch
- Anodizing	1.44	MJ/m^2	0.163	kg/m^2
- Painting	Negligible	-	Negligible	-
- Curing primer	117	MJ/batch	13.221	kg/batch
Operational phase	$1.72 \cdot 10^{-3}$	MJ/(kg·km)	$0.124 \cdot 10^{-3}$	kg/(kg · km)
End of life (Recycling)	34.9	MJ/kg	3.94	kg/kg

Table 2.2: Summary machined aluminium - Al7050 T7451

Stage	Larger ribs Al 7050 T7451			
	Energy	Unit	CO_2-eq	Unit
Raw material production	201	MJ/kg	22.71	kg/kg
Transport:				
- Road	0.94	MJ/(tonne·km)	0.072	kg/MJ
- Air (Short haul)	12	MJ/(tonne·km)	0.072	kg/MJ
- Air (Long haul)	6.5	MJ/(tonne·km)	0.072	kg/MJ
Part Manufacturing:				
- Storage	Negligible	-	Negligible	-
- Machining (coarse)	2.12	MJ/kg removed	0.240	kg/kg removed
- Machining (fine)	16.5	MJ/kg removed	1.865	kg/kg removed
- NDI (die penetrant)				
> Preparation	194	MJ/batch	21.922	kg/batch
> Oven	30.8	MJ/batch	3.48	kg/batch
- Anodizing	1.44	MJ/m^2	0.163	kg/m^2
- Painting	Negligible	-	Negligible	-
- Curing primer	117	MJ/batch	13.221	kg/batch
Operational phase	$1.72 \cdot 10^{-3}$	MJ/(kg·km)	$0.124 \cdot 10^{-3}$	kg/(kg·km)
End of life (Recycling)	34.6	MJ/kg	3.91	kg/kg

2.2.2. Aluminium sheet metal forming

When it comes to aluminium sheet forming, most of the numbers will be similar to what was seen in the machining subsection. Some changes will occur however since the process flows are different in the manufacturing part, as seen as well from Figure 2.2.

Raw material production

This first step is identical to what was seen before as well, and that is due to the fact that the aluminium is processed the same way. As a result, this step will not be discussed further. An assumption will have to be made here regarding the materials used. Typically, the selected aluminium alloys have limited use for forming processes [3]. It will be assumed for the purpose of this thesis however that they are used for the forming of the parts.

Assumption

Al7075 T73 and Al7050 T7451 can be used for sheet forming processes in the context of this thesis.

Transport

The aluminium used will be transported via the same means regardless of its form (ingots/billets/sheet). Therefore, this step remains the same as before as well.

Part manufacturing

In this step, some differences appear. Firstly, as opposed to the machined aluminium where the blocks of aluminium can be sent directly to be machined, in the case of forming, these blocks must first be turned into sheets. This is done via rolling, which was shown in chapter 1, Figure 1.8. Data was found for both cold rolling and hot rolling for energy consumption in a report created for the U.S. Department of Energy in 2007 [5]. According to this, hot rolling could use up to 2.232 MJ of energy per kg of rolled material, whereas cold rolling 2.304 MJ again per kg of rolled material. The CO_2-eq produced as a result would be of 0.252 kg/kg or 0.260 kg/kg for the two processes respectively. This information was also directly verified using a study by Ecofys, Fraunhofer Institute for Systems and Innovation Research and Öko-Institut [18]. Here, the reported value range gives a maximum CO_2 production for rolling processes of roughly 235 kg/tonne of product, or 0.235 kg/kg as it was also estimated above using the energy reported and the electricity mix. For storage, since aluminium does not have any special requirement, the energy consumption was considered negligible.

The next step in the process is the cutting of the sheets into the desired shapes. This can be done using a plasma cutter [6] or mechanical cutting. For the sake of discussion, in order to see what energy might be required for such a process, a similar plasma cutter to that seen in the paper was found on IGoldenCNC's website[4], where the specs of the machine were taken from. Plasma cutting is however not a process typically used in such processes due to the thermal impact that it can have on the material surrounding the cut area. Similarly, if such a process would be used later on in composites, similar problems could be encountered, and the area around the original cut would have to be trimmed to remove the affected material. Considering that the cutter is a 3 phase, 200 A, 140 V machine, the power was calculated at 48 kW. Such a machine would use 172.8 MJ of energy per hour, and the CO_2-eq emissions are calculated at 19.526 kg/h. On the other hand, the use of mechanical cutting would result in negligible amounts of energy use.

Moving onto the forming processes, initially three different variations were considered, press brake, rubber forming and roll forming. In terms of energy consumption and emission, these processes have similar numbers. It will be mentioned however that typically rubber forming is more common for the manufacturing of wing ribs (since it allows for the manufacturing of double curved parts and uses higher forces than the press brake bending process). For the roll forming process on the other hand it has been decided to leave it out due to the fact that the ribs to be manufactured have a relatively complex geometry which may be more than what this particular process can handle. Research was done into press brakes and their energy consumption. An alternative using 7.5 kW of power was found [5]. In order to determine the energy it is required to know the amount of time that the machines are used for. For a single part, these processing times are negligible since the deformation is almost instant. Even if a large number of parts would be considered, the largest amount of time in such a process would be for placing the sheets in the presses, during which the machines are inactive and therefore not using any electricity. As it was seen in the case of the machined parts, there are certain processes in the chain which involve heat, and which are very costly from the energy point of view. By comparison, any estimation of energy at this step in the manufacturing process would not get anywhere close to these values and therefore they will be considered negligible. This is also information obtained during discussions about sheet forming with employees from GKN **[Jos Thoolen, personal communication, 13.06.2022]**. For the sake of discussion, let us assume a process time of 1 minute per part (not including the sheet placement and removal from the press). If the machine would function at full power, which is most likely not the case, the total energy consumption would be of around 0.125 kWh or 0.45 MJ per part. This, compared to heating processes in excess of 200 MJ is indeed negligible.

Assumption
Energy of forming processes is negligible by comparison to heating processes further down the line.

Just like for machined parts, after the manufacturing stage, NDI has to be conducted on the parts. When it comes to sheet formed products, the NDI is typically limited to visual inspection **[Marc Koetsier, personal communication, 26.08.2022]**. After NDI, anodising and painting are required and once again these are done the same way as before, thus the numbers don't change here either.

One additional step when considering sheet forming is assembly. As opposed to machining where the integral part can be obtained from a block of metal, sheet forming is limited in the types of geometries it can create. In the case of wing ribs for instance, I-beam or T-beam profiles could not be obtained in one go, but they would require two symmetrical beams that would be assembled back to back, resulting in the final geometry (excluding the reinforcements). A sketch of the rib (as designed for thermoplastic

[4] https://www.igoldencnc.com/Muti-functio-Plasma-machine.html
[5] https://www.tiptopmfg.com/product/hydraulic-press-brake/

materials) can be seen for Figure 2.5.

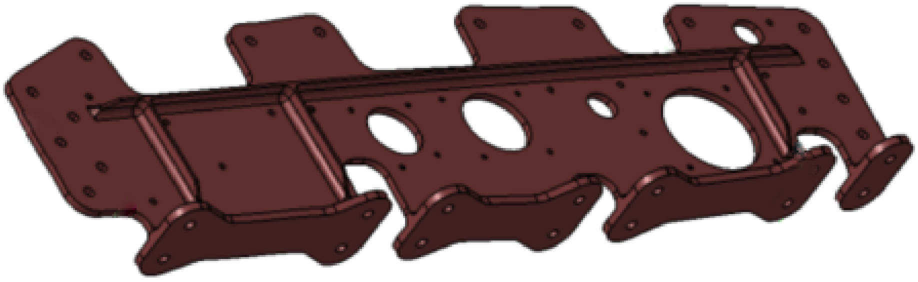

Figure 2.5: Sketch of wing rib geometry. Image credits: GKN Fokker

As it was discussed as well in chapter 1, there are a number of different assembly methods that could be considered. In the case of the aluminium alloys considered, welding is unfortunately not an option since their weldability is poor [3]. This leaves only adhesive bonding and mechanical fastening. For mechanical fastening, the only energy requirements could come from the pneumatic tools used, however as discussed previously for the paint guns as well, this is difficult to estimate the energy requirement of and also it is considered to be negligible regardless. These processes would involve drilling the holes, deburring and adding the rivets. For adhesive bonding on the other hand, the processing steps include degreasing of the part, followed by abrasion, application of the adhesive and lastly curing of the adhesive. Out of these steps, the only one requiring a more significant energy input would be the curing phase once again which in some cases is done at a raised temperature. One of the most used adhesive for metals and especially for aluminium is epoxy [42]. One can also distinguish here between two types of adhesives: paste and film adhesives. In the case of paste adhesives, according to blogs about the use of epoxy, the time required for curing if a temperature of 10°C is used, is of about 18 hours[6] and for each 10°C increase in cure temperature, the time is roughly halved[7]. Based on temperature ranges which were used in other research for testing the degree of cure and properties of such adhesives [35], it can be assumed for convenience that if adhesive bonding would be used, 50°C could be an appropriate temperature choice. Using all of the sources found, at this temperature roughly 1 hour would be required for curing. These adhesives are however not typically used in aerospace structures, but rather films are a more common choice, which are known to cure at roughly 120°C **[Marc Koetsier, personal communication, 01.09.2022]**. If a similar heating oven as the one used for drying the parts during NDI of the machined aluminium parts (same temperature and same power setting), using Equation 2.2, and replacing this time the ΔT by 100°C, the result is a total of 92.184 MJ of energy per batch, and an equivalent 10.41 kg of CO_2-eq emissions.

Assumptions

- *For curing the adhesive, a similar oven to that used for NDI is considered.*
- *Epoxy adhesives are used for adhesive bonding.*
- *A cure temperature of 120 degrees is chosen for the adhesive.*

Operational life

The operational life is dependent only on the weight of the components and the travelled distance and not the material. Since the numbers found before were given as a function of these two components, they will not change for this section.

End of life

Since the materials are the same, and the same assumptions are also maintained for the parts manufactured through sheet forming, the numbers for recycling also remain the same as previously described.

[6] https://www.euclidchemical.com/company/blog/archive/5-tips-for-applying-epoxy-coatings-in-cold-weather/
[7] https://www.permabond.com/resource-center/consistent-component-epoxy-curing/

Summary
Just like for the previous section, a summary is provided in Table 2.3 and Table 2.4 for the processes described.

Table 2.3: Summary sheet formed aluminium - Al7075 T73

Stage	Small ribs (thickness <100mm) Al 7075 T73			
	Energy	**Unit**	**CO_2-eq**	**Unit**
Raw material production	203	MJ/kg	22.94	kg/kg
Transport:				
- Road	0.94	MJ/(tonne·km)	0.072	kg/MJ
- Air (Short haul)	12	MJ/(tonne·km)	0.072	kg/MJ
- Air (Long haul)	6.5	MJ/(tonne·km)	0.072	kg/MJ
Part Manufacturing:				
- Storage	Negligible	-	Negligible	-
- Rolling				
> Cold	2.304	MJ/kg	0.260	kg/kg
> Hot	2.232	MJ/kg	0.252	kg/kg
- Cutting				
>Plasma	172.8	MJ/hour	19.526	kg/hour
>Mechanical	Negligible	-	Negligible	-
- Forming (press brake)	Negligible	-	Negligible	-
- NDI (visual inspection)	Negligible	-	Negligible	-
- Anodizing	1.44	MJ/m^2	0.163	kg/m^2
- Painting	Negligible	-	Negligible	-
- Curing primer	117	MJ/batch	13.221	kg/batch
- Assembly	92.18	MJ/batch	10.41	kg/batch
Operational phase	$1.72 \cdot 10^{-3}$	MJ/(kg·km)	$0.124 \cdot 10^{-3}$	kg/(kg·km)
End of life (Recycling)	34.9	MJ/kg	3.94	kg/kg

Table 2.4: Summary sheet formed aluminium - Al7050 T7451

Stage	Larger ribs Al 7050 T7451			
	Energy	**Unit**	**CO_2-eq**	**Unit**
Raw material production	201	MJ/kg	22.71	kg/kg
Transport:				
- Road	0.94	MJ/(tonne·km)	0.072	kg/MJ
- Air (Short haul)	12	MJ/(tonne·km)	0.072	kg/MJ
- Air (Long haul)	6.5	MJ/(tonne·km)	0.072	kg/MJ
Part Manufacturing:				
- Storage	Negligible	-	Negligible	-
- Rolling				
> Cold	2.304	MJ/kg	0.260	kg/kg
> Hot	2.232	MJ/kg	0.252	kg/kg
- Cutting				
>Plasma	172.8	MJ/hour	19.526	kg/hour
>Mechanical	Negligible	-	Negligible	-
- Forming (press brake)	Negligible	-	Negligible	-
- NDI (visual inspection)	Negligible	-	Negligible	-
- Anodizing	1.44	MJ/m^2	0.163	kg/m^2
- Painting	Negligible	-	Negligible	-
- Curing primer	117	MJ/batch	13.221	kg/batch
- Assembly	92.18	MJ/batch	10.41	kg/batch
Operational phase	$1.72 \cdot 10^{-3}$	MJ/(kg·km)	$0.124 \cdot 10^{-3}$	kg/(kg·km)
End of life (Recycling)	34.6	MJ/kg	3.91	kg/kg

2.2.3. Thermoset Epoxy-CFRP prepreg composite

Switching the focus to composites, the first one on the list is a thermoset Epoxy-CFRP version, and more specifically produced using prepregs. Prepregs refer to fabrics which have already been impregnated with resin before making it to the factory where the parts will be produced.

Raw material production

Starting once again with the raw material production, in the case of prepreg, the independent steps for its production are not looked at in detail, but rather the embodied energy for the product reaching the factory is considered straight away. This is taken from the databases in EduPack [3]. The laminate from the database is reported to have a [0/+45/-45/90]s quasi-isotropic layup using high strength carbon fibre. The fibre fraction volume is given as a range from 0.55 to 0.65.

Assumptions

- *The thermoset laminate is a [0/+45/-45/90]s quasi-isotropic layup using high strength carbon fibre with fibre fraction volume between 0.55 and 0.65.*
- *Autoclave curing between 115-180°C, 6-7 bar.*

For this prepreg, the embodied energy is reported at 723 MJ of energy per kg. As per the assumptions made in the sections for aluminium, the data for CO_2-eq will not be taken directly from this database, but will be calculated using an energy mix conversion factor. Since the composite materials are brought from the USA, a conversion factor of 0.141 kg/MJ is used as per the region electricity mix data. As a result, for the prepreg material there are 101.943 kg of CO_2-eq produced per kg of prepreg.

Transport

For the transport of the composites, the same rules apply as in the case of aluminium. As a result, the numbers here remain almost identical. The only additional element that needs to be considered is cooling. Since the prepregs are already impregnated with resin but not fully cured, it is important to make sure that the resin does not fully cure before the material enters production. This is achieved by ensuring both a cold storage (to be discussed in the coming paragraphs) and a cooled transportation. In order to keep the data together, both the cooled storage and the transport will be discussed together and the numbers for both will be provided in the next paragraphs.

Part manufacturing

In the case of thermosets, as it was described previously, the storing temperature becomes important. Additionally, even at low temperatures, the prepregs still have a set shelf life. Taking as example the Epoxy prepregs produced by Gurit [23], these have a maximum shelf life of 18 months if stored at -18°C. A first attempt at calculating the energy consumption for keeping the composites cool was done by attempting to scale up a freezer used in such applications to the volumes of a refrigeration building. Using a study done by EnergyStar on 354 models of freezers[8], it was found that on average, a household freezer with a maximum power between 80 W and 900 W will use between 11.42 kWh (41.112 MJ) and 54.08 kWh (194.688 MJ) of energy per month. To cross check this information and also be able to choose an appropriate value for the energy from this range, an example of industrial freezer was found. This was a freezer with a temperature capability of -34°C and 0.57 m^3 of volume. The specifications of this freezer bring it to a power of 800 W. This is in the high end of the ranges mentioned in the EnergyStar study, and therefore the choice was to also take the high end of the range for the monthly energy consumption. The next choice which had to be made was for the refrigeration time of the composites. This is a difficult assumption to be made since it depends heavily on the production capabilities of the factory, the demand and the amount of material ordered in the first place. Considering what was also mentioned in chapter 1 regarding material waste when it comes to composites, it was decided to go for the full 18 month shelf life. The reasoning for this is as follows: it is assumed that if a large amount of material is available, with due dates in increasing order, the first material which will go into production will be the one that is the closest to its due date. This way, the amount of waste is limited. Considering that unfortunately material still goes to waste at the end of the day, this means that a large part of the composites will actually stay in refrigeration units at least until their shelf life is over, thus the freezer would have to constantly provide a cool environment for them for a minimum of 18 months. An additional step is made here and it is also assumed that in order to avoid energy waste, the materials which are out of date are removed from the storage units and replaced with new ones.

Assumptions

- *Maximum energy consumption of a freezer per month is of roughly 54.08 kWh (194.688 MJ).*
- *The refrigeration time for thermoset composites is of 18 months.*

With this in mind, the energy consumption of the freezer for the entire 18 months would come at 973.44 kWh (3.504 GJ). It is already visible from this that when the scale up will be done, the amount of energy required for the composites would be extremely high. For the scale up itself, the first step is to take the equation for energy transfer as it was seen in Equation 2.1. For convenience, this is provided again below:

$$Q = m \cdot c \cdot \Delta T \tag{2.7}$$

It is seen from here, that since c is constant for air and so is the expected change in temperature from room temperature to the end value of -18°C (including any losses to the environment), the energy Q scales linearly with the mass of air m present in the freezer. Considering the difference in volume between a freezer such as the one found above (approximately 0.57 m^3) and the volume of a building (say 3500 m^3 for example, similar to the facility at GKN Fokker Hoogeveen), it is clear that the energy scale up will result in an immense amount of energy which would hardly be sustainable economically and environmentally. It was understood that the probable reason behind this result is that the two refrigeration

[8] https://ecocostsavings.com/freezer-wattage-energy-efficient/#how-many-watts-does-a-freezer-use

units considered, there is a fundamental working principle difference. While a freezer uses induction in order to cool the items inside (cooling the walls and the air within as a result of this), a large building will use air conditioning units with various BTU (British Thermal Unit) values. While data on refrigeration units of companies was not found, an easy example of a cooled building could be found while looking at indoor skiing facilities. Taking Ski Dubai as a prime example, a study was found which estimated the energy consumption of the facility yearly. According to this study, considering the outside temperature and the inside required temperature (average yearly ΔT of 30°C), the total yearly consumption would arrive at a maximum value of 915 MWh, excluding the additional energy required via induction to the ground for creating and maintaining the snow layer [44]. The surface area of the ski resort is of approximately 22500 m^2 [9]. From images of the skiing area, the height of the building can roughly be taken at 10 m, resulting in a volume of about 225000 m^3. When choosing an air conditioning unit for a room/building, the power is mainly chosen based on the volume of the room/building, the climate and sun exposure which dictate the potential energy loss. Dividing the energy found above for the building by the estimated volume, one obtains 4.067 kWh/(year·m^3), equivalent to 14.64 MJ/(year·m^3). For the CO_2-eq, this would mean about 1.654 kg/(year·m^3). The original method considered although not useful for the large building comes in handy for the transportation stage since the refrigeration units added on trucks are not using air conditioning units, but a compressor running on diesel [30]. This is similar to the freezer unit considered initially, and therefore a scale up of that one would be appropriate for transportation purposes. The energy found would therefore be 94.88 kWh/(month·m^3). Since transportation is not going to last months, the units will be converted to something more appropriate, in the range of hours: 0.468 MJ/(hour·m^3) (using an average of 30.4 days per month). Since the energy is provided by a compressor running on diesel, the same conversion factor will be used as for transport in this situation for calculating the CO_2-eq emissions, which come out at 0.0337 kg/(hour·m^3).

Since refrigeration was needed for these materials, before they can be put in use, they need to be taken out and left to thaw. This step of the process is assumed to be done at room temperature, only once per material, and therefore no energy input is required.

Assumption

For thermoset composites, thawing occurs at room temperature with no energy input, and thawing is performed only once.

The next step prior to layup is cutting. This is assumed to be done with the same cutter that was used previously for metals (both plasma and mechanical cutting kept in for reference, however it should be noted that plasma cutting is not done in practice. It has been kept in the tables however as an example of how high the cutting energy could go if such a process would in theory be chosen, but also as an example of "not like this"), and therefore the numbers remain the same.

Once the material is cut, the layup can begin. For this, two options are considered, a manual one and an automated one (via AFP- automatic fibre placement or ATL - automatic tape laying). In the case of hand layup, there is no energy consumption, apart perhaps from the lasers used for guidance in order to ensure the fibres are placed in the correct position and warm tools for tackiness. These however are low power consumers especially compared to other processes and will not be considered in the analysis. For the ATL and AFP processes, the power required comes mostly from the robots/robotic arms used, and their control units. For estimating the energy consumption in this case, the robot arm used by GKN Fokker was taken for example. For AFP this is a Fanuc Robotics R2000IB 100b robot arm together with its B-cabinet controller. The arm and the cabinet have power ranges of 380-575 V and 380-415 V respectively[10]. Once again compared to other processes discussed earlier, these can be seen to be negligible. Considering advice given by employees at GKN Fokker as well **[Maarten van Cappellen, personal communication, 04.06.2022]**, this stage will be kept as such. For ATL on the other hand, the machine considered as an example is a Boikon Falco (ATL300). The manufacturer advertises this as the first continuous ultrasonic machine[11], and exact specifications of the power and energy consumption are not available. This is a limitation for this study, however based on the numbers observed for the robots used in AFP, it will be assumed that a similar situation will be seen in ATL,

[9] https://en.wikipedia.org/wiki/Ski_Dubai

[10] https://www.fanuc.eu/uk/en/robots/robot-filter-page/r-2000-series

[11] http://www.fiberplacement.com/automated-tape-laying/#/thermoplastic-composites/

thus the energy consumption will be taken as negligible as well, especially since these processes are typically rather slow and will use little electrical power.

Assumption

Robots used in the ATL and AFP processes use a negligible amount of energy.

Once the layup is complete, the part needs to go in the autoclave at the specified temperatures and pressure in order to completely cure it. According the the database from EduPack, for the selected prepreg, for a temperature range between 115-180°C and pressure range between 6-7 bar, the energy consumed in the autoclave will be of 23 MJ/kg, and the CO_2-eq emissions are calculated at 2.60 kg/kg.

The trimming of the part after curing will be done with the same machines which were used for cutting. For ease of calculations, the energy of these two processes will therefore be combined. An amount of time will need to be estimated for the two processes together and the total energy will be given in the cutting phase.

Assumption

Cutting and trimming are done with the same machine and therefore the total energy use will be bundled in one stage only (cutting).

Just like for metals, NDI will be required for composites once the part is done as well. In the case of composites however, the NDI method chosen in ultrasonic testing. More specifically, two types of ultrasonic testing are considered here, A-scans and C-scans especially since they are the ones used at GKN Fokker Hoogeveen as well. The provider of the scanning system is USL (Ultrasonic sciences LTD), and the system is a twin tower one, with a power specification of 20 kW. According to an article on the development of ultrasonic systems for C-scans in composites [9], such techniques will require a minimum of 10 kW of power when in use. In order to determine the energy, the scanning time will be needed per part. Considering that the machine will have a standard scanning speed, the amount of time that it would take for it to scan a part will scale up approximately linearly with the part size (of course unless the geometry of the part is very complex, in which case some additional time may be added). During conversations with NDT specialists at GKN **[Dirk Barelds, personal communication, 22.07.2022]**, it was found that for a rectangular part with an area of approximately 0.3 m^2 (1 m length and 0.3 m width), a scan time of roughly 20 minutes will be required. This translates to an energy of 6.67 kWh or 24 MJ, taking into account the full power of the machine of 20 kW. In order to get a specific energy consumption relative to the surface area, dividing this number by the 0.3 m^2 results in 80 MJ/m^2. It was also found that during production, sometimes an A scan will be required for the parts as well, however no further details were found about it. In the absence of data, it will be assumed however that a similar scanning time is required and also that a similar powered machine is used for the scan, resulting in the same numbers for this scan as well. The CO_2-eq emissions are calculated at 9.04 kg/m^2.

Assumptions

- *Scanning time for ultrasonic testing increases linearly with part surface area.*
- *A scan machinery is similar to C scan machinery, and scanning times are similar for equally sized parts.*

Operational life

For the operational life, no changes are made from the previous sections.

End of life

In the case of thermoset composites, recycling is difficult. They can however be combusted for energy, which is also what is done in the industry **[Wesley McNulty, personal communication, 22.06.2022]**. Using the EduPack database for the selected prepreg material, data was found for the combustion energy at 32.9 MJ/kg of material combusted, and a CO_2-eq emission of 3.33 kg/kg. Here it is important to notice that the CO_2-eq value is taken directly from the database rather than calculating it as it was done before. This is due to the fact that this process is different from what was seen so far. All previous processes used electricity or various fuels in order to operate. They were consumers, and the CO_2-eq was calculated based on the energy consumption of the process. In this situation, combustion of the prepregs is meant to generate energy rather than consume it, and therefore the CO_2-eq is defined in the database as the emissions during the combustion.

Assumption

In the case of combustion of materials, the CO_2-eq are taken directly from the database since these processes are producers of energy rather than consumers as for other processes described.

Summary

Once again, as for the previous materials, a summary table is set up in Table 2.5, showing all data for the CFRP Epoxy prepreg part manufacturing.

Table 2.5: Summary thermoset Epoxy-CFRP prepreg

Stage	CFRP Epoxy prepreg			
	Energy	**Unit**	**CO_2-eq**	**Unit**
Prepreg production	723	MJ/kg	81.70	kg/kg
Transport:				
- Road	0.94	MJ/(tonne·km)	0.072	kg/MJ
- Air (Short haul)	12	MJ/(tonne·km)	0.072	kg/MJ
- Air (Long haul)	6.5	MJ/(tonne·km)	0.072	kg/MJ
- Cooling	0.468	MJ/(hour·m^3)	0.0337	kg/(hour·m^3)
Part Manufacturing:				
- Cooled storage	14.64	MJ/(year·m^3)	1.654	kg/(year·m^3)
- Thawing	-	-	-	-
- Cutting				
> Plasma	172.8	MJ/hour	19.526	kg/hour
> Mechanical	Negligible	-	Negligible	-
- Layup				
> Hand layup	-	-	-	-
> ATL/AFP	Negligible	-	Negligible	-
- Autoclave (incl. bagging)	23	MJ/kg	2.60	kg/kg
-Trimming	Incl. in cutting	-	Incl. in cutting	-
- NDI				
> A-scan	80	MJ/m^2	9.04	kg/m^2
> C-scan	80	MJ/m^2	9.04	kg/m^2
- Painting	Negligible	-	Negligible	-
- Curing/drying	117	MJ/batch	13.221	kg/batch
Operational phase	$1.72 \cdot 10^{-3}$	MJ/(kg·km)	$0.124 \cdot 10^{-3}$	kg/(kg·km)
End of life (Combust for energy)	-32.9	MJ/kg	3.33	kg/kg

2.2.4. Thermoset Epoxy-CFRP RTM composite

Raw material production
This time, for the raw material production two separate components are considered, the epoxy and the carbon fibre. The reason this time it is different from the prepreg is because the fibres are layed down and impregnated directly in the factory, and therefore it is considered part of the analysis, whereas previously, the prepregs were manufactured outside the factory. Starting with the epoxy, a number of different options were available in the databases of EduPack. For the purpose of this report, the unfilled epoxy was chosen since this is also closer to what is used in the manufacturing processes at GKN. For this, the embodied energy is found as 135 MJ/kg and the CO_2-eq emissions are calculated at 19.035 kg/kg. For the carbon fibre on the other hand, the embodied energy was found for three different options, one was for primary fibre production, second for creating fabrics from the fibres and third for creating prepregs using these fabrics. The energies for these three options were 300 MJ/kg, 2.73 MJ/kg and 42 MJ/kg respectively, with equivalent CO_2-eq emissions at 42.3 kg/kg, 0.385 kg/kg and 5.922 kg/kg respectively. All numbers are calculated once again using the conversion factor of 0.141 found for North America.

Transport
For the transport of these materials, cooling systems will be required once again, since the resin is still capable of curing, except when it comes as a two component resin. In aerospace however mostly one part resins are used **[Wesley McNulty, personal communication, 22.06.2022]**. The same numbers calculated previously will be used here as well.

Part manufacturing
The first step that differs comes after layup. In the case of resin transfer moulding, the first step after layup is to make a preform of the part (using a matched die). This is done by applying heat and pressure. The energy consumption was found in the same database as the one used for the prepregs from the previous section. This is 10.6 MJ/kg and the CO_2-eq emissions are calculated at 1.198 kg/kg.

> Assumption
>
> *In the RTM processing, the preforming energy is taken from the EduPack database for the quasi-isotropic prepreg selected previously.*

Once the preform has been created, the next step is to infuse the part with the resin via RTM. For this step, primary data from processes at GKN was obtained in the absence of databases on RTM in EduPack. According to these numbers, from a total of 2111.60 kWh consumed for the full infusion of a part, a total of 69% was used for heating up the tools, 11% for the injection itself, and the remaining 20% were left for the curing stage. The process was recorded over a total duration of 20 hours, thus indicating a total energy consumption of 7.6 GJ, with a rate of 380 MJ/hour. The CO_2-eq emissions are calculated at 42.94 kg/hour. Although these processes already included a curing phase, post curing in the oven might also be required. If this is the case, additional numbers were found for this in EduPack, with 23 MJ/kg and 2.60 kg/kg of CO_2-eq emissions. From this step onward, the remaining ones are identical to those from the Epoxy prepreg part manufacturing.

Operational life
The operational life does not change.

End of life.
For the end of life, since the materials were separated in the primary material stage, their end of life were considered separately as well. This is however only for the situation where material has to be recycled without having gone through the processing steps above (in other words if the shelf life expired or for whatever other reason which may require the material to be recycled in it's non-processed form). For parts which have already been processed, the recycling will be done similar to what was seen for parts out of prepregs, and that is by combustion, with the numbers remaining the same. For unfilled epoxy, the combustion energy was found at 31.5 MJ/kg, with 2.54 kg/kg CO_2-eq emissions, while for

carbon fibres (high strength), the energy found was 33.6 MJ/kg with 3.76 kg/kg CO_2-eq emissions.

Summary
The summary of all the data for this processing route can be seen in Table 2.6 below.

Table 2.6: Summary thermoset Epoxy-CFRP RTM

Stage	CFRP Epoxy RTM			
	Energy	**Unit**	**CO_2-eq**	**Unit**
Epoxy production (unfilled)	135	MJ/kg	15.255	kg/kg
Carbon fibre:				
- Primary	300	MJ/kg	33.9	kg/kg
- Fabric	2.73	MJ/kg	0.308	kg/kg
- Prepreg	42	MJ/kg	4.746	kg/kg
Transport:				
- Road	0.94	MJ/(tonne·km)	0.072	kg/MJ
- Air (Short haul)	12	MJ/(tonne·km)	0.072	kg/MJ
- Air (Long haul)	6.5	MJ/(tonne·km)	0.072	kg/MJ
- Cooling	0.468	MJ/(hour·m^3)	0.0337	kg/(hour·m^3)
Part Manufacturing:				
- Cooled storage	14.64	MJ/(year·m^3)	1.654	kg/(year·m^3)
- Cutting				
> Plasma	172.8	MJ/hour	19.526	kg/hour
> Mechanical	Negligible	-	Negligible	-
- Layup (hand layup)	Negligible	-	Negligible	-
- Preform (matched die)	10.6	MJ/kg	1.198	kg/kg
- RTM infusion	380	MJ/hour	42.94	kg/hour
- Autoclave (post curing)	23	MJ/kg	2.60	kg/kg
- Trimming	Incl. in cutting	-	Incl. in cutting	-
- NDI (C-scan)				
> A-scan	80	MJ/m^2	9.04	kg/m^2
> C-scan	80	MJ/m^2	9.04	kg/m^2
- Painting	Negligible	-	Negligible	-
- Curing/drying	117	MJ/batch	13.221	kg/batch
Operational phase	$1.72 \cdot 10^{-3}$	MJ/(kg·km)	$0.124 \cdot 10^{-3}$	kg/(kg·km)
End of life:				
- Epoxy (combust)	-31.5	MJ/kg	2.54	kg/kg
- Carbon fibre (combust)	-33.6	MJ/kg	3.76	kg/kg
- Prepreg (combust)	-32.9	MJ/kg	3.33	kg/kg

2.2.5. Thermoplastic PEKK-CFRP hot-press consolidated composite

Raw material production
For this material, since a specific prepreg option was not found in the databases of EduPack, a similar approach to that seen for the RTM Epoxy CFRP part was taken. The resin and the fibres were looked at separately. The fibres are still carbon fibres so the numbers remain the same as those seen in Table 2.6. For the resin on the other hand, this time PEKK was looked into. According to the database of EduPack, this material has an embodied energy of 333 MJ/kg. Considering once again that it is produced in the USA, the CO_2-eq emissions are calculated as 46.953 kg/kg. A final comment here is that for this process flow the thermoplastic materials arrive at the factory as prepregs, and therefore for the calculations which will need to be done in chapter 3, the prepreg values of carbon fibre will be

required in order to account for this.

Transport
The transportation means remain once again the same, and therefore the numbers do not change from what was seen in the previous tables, except the cooling element which is not required this time.
Part manufacturing
In the case of thermoplastic materials, the storage is not an issue such as in the case of thermosets, since thermoplastics do not cure, and therefore have a virtually infinite shelf life. The materials do however need to be sheltered from humidity and UV, yet this is similar to the case of aluminium alloys, and as a result, for this section, the energy will be considered negligible. Additionally, as mentioned previously as well, some of the processes that are considered have the energy of running the factory (including the ventilation system) included in the final value. Moving onto cutting, this can be done using the same machinery as before. One aspect that should be mentioned is that depending on the type of layup chosen later on, the cutting may be included in that process. Taking for example manual layup, here the cutting has to be done as it was shown for the thermoset materials. For automated processes such as ATL and AFP, the tapes are laid down by a robot and cut on the spot. In this case, the energy used would be different, but in this project, the cutting is combined as well with the final trimming after the part is done, and therefore it will not be passed as negligible.

Assumption

Usually, for automated processes (ATL/AFP), cutting is included in the process and could be passed as negligible for energy consumption. For this project, cutting is however clustered with final trimming of the part and therefore the energy consumption is considered separately from layup.

For the layup, once again there are two options, either hand layup in which the only energy would be coming from ultrasonic welding which is needed for the layers to stick to each other. This is a negligible energy consumer since in many cases the welding will be done by spot welding so the amount of time in which the tools are powered is very short. For ATL and AFP, the same numbers as those seen for thermoset apply, since very similar machines can be used (considering that the thermoplastic joining is done with ultrasonic welding during layup). The next step for thermoplastics would be creating a preform (only done sometimes). If the same numbers are used as in the case of RTM, 10.6 MJ/kg of energy will be used and 0.849 kg/kg of CO_2-eq will be emitted.

Thermoplastic materials do not cure, however they need to be consolidated in order to obtain the final part shape. This is done by applying pressure and high temperature. Since autoclaves could achieve this but use a high amount of energy in the process, another approach is to use a heated press for out-of-autoclave consolidation, which is also what is done at GKN Fokker in Hoogeveen, and is the process which was considered for this thesis. The exact energy consumption for such processes was not found in any database, and as a result, primary data from the manufacturing of rib 14 of WoT was used directly. The press itself uses energy too, however just as for the previous processes considered for thermosets, the energy required for heating the part up is the most important one. The heating in this case was achieved by the use of heating rods. Each of the rods had a total power of 4 kW, and data was recorded at 10 second intervals throughout the consolidation process. This data included the percentage of the total power that was used at a certain time, for each of the 18 rods used. In order to find the energy consumption in this case, the percentage of the power was multiplied by the maximum 4 kW power, and then by 10 since the data was taken over 10 second intervals as mentioned before. This was repeated for all 10 second intervals of each rod. The energies per rod were found and then summed up for all rods in order to find the final energy value. The entire process can be summarised by means of equations as follows:

$$E_{interval_n} = \%_n \cdot 4kW \cdot 10s \tag{2.8}$$

$$E_{rod_m} = \sum_{i=1}^{n} E_{interval_i} \tag{2.9}$$

$$E_{total} = \sum_{i=1}^{18} E_{rod_i} \tag{2.10}$$

In equations Equation 2.8 through Equation 2.10, $\%_n$ represents the percentage of energy used on the n^{th} 10 second interval for one rod alone, and m is the rod number, going from 1 to 18. Conducting these calculations and subsequent unit conversions, the total energy was calculated at 82 MJ/rib, and the equivalent CO_2 emissions come out at 9.266 kg/rib.

Once consolidation is complete, the only remaining steps are final trimming, NDI and then painting. These processes remain identical to what was seen in the previous tables for thermosets.

Operational life

Once again, the operational life remains the same since it is not dependent on anything but the weight of the part and the distance travelled.

End of life

Recycling for thermoplastics is what makes them interesting in the industry, since as opposed to epoxies, thermoplastic resins can be remelted and used again with an acceptable reduction in their properties. They can of course also be combusted for energy similar to the carbon fibres. For recycling, the energy was found in EduPack databases as 113 MJ/kg, with an equivalent CO_2 emission of 12.769 kg/kg, and combustion was found to produce 31 MJ/kg of energy and 3.01 kg of CO_2. The numbers for recycling carbon fibre (combustion) remain the same as before. As a side note, in order to obtain the total energy usage for recycling in a prepreg, there are two options. One either assumes that the resin and the fibres are both combusted, in which case the energy would be the total energy produced by the combustion (sum of resin and fibres), or alternatively, the matrix and fibres could be recycled together. An example of this is a rotorcraft access panel created by GKN Fokker [56], which can be seen in Figure 2.6 (flying component of Bell v280 Valor).

Figure 2.6: Bell v280 Valor, rotorcraft access panel. Photo credits: GKN Fokker [56]

For such a component, the approach that is taken is to first grind the part containing the continuous fibres into pieces containing fibres with lengths up to 10 mm or even 1 mm **[Marc Koetsier, personal communication, 26.08.2022]**. PEKK resin can then be added to the mixture in order to ease processing. The final mixture can be heated up and press formed into a new component. According to estimates from GKN Fokker, an aircraft with 20 ribs per wing could generate roughly 110 kg of thermoplastic composite material with a value of up to €14000. The recycling process would result in a reduced energy consumption and CO_2 emissions for the production of subsequent parts out of this material. An examplification of the process for recycling PEKK can also be seen in Figure 2.7.

Figure 2.7: Recycling steps. Image credits: GKN Fokker

The exact energy consumption for this process was however not known, and therefore the exact method for calculating the recycling energy and CO_2 emissions will be described in chapter 3 during the case study.

Summary
The final summary table for the thermoplastic material manufacturing can be seen in Table 2.7 below.

Table 2.7: Summary Thermoplastic PEKK-CFRP out-of-autoclave consolidation

Stage	**CFRP PEKK**			
	Energy	**Unit**	**CO_2-eq**	**Unit**
PEKK production (unfilled)	333	MJ/kg	46.953	kg/kg
Carbon fibre:				
- Primary	300	MJ/kg	42.3	kg/kg
- Fabric	2.73	MJ/kg	0.385	kg/kg
- Prepreg	42	MJ/kg	5.922	kg/kg
Transport:				
- Road	0.94	MJ/(tonne·km)	0.072	kg/(tonne·km)
- Air (Short haul)	12	MJ/(tonne·km)	0.072	kg/(tonne·km)
- Air (Long haul)	6.5	MJ/(tonne·km)	0.072	kg/(tonne·km)
Part Manufacturing:				
- Storage	Negligible	-	Negligible	-
- Cutting				
> Plasma	172.8	MJ/hour	19.526	kg/hour
> Mechanical	Negligible	-	Negligible	-
- Layup				
> Hand layup	Negligible	-	Negligible	-
> ATL/AFP	Negligible	-	Negligible	-
- Preform (matched die)	10.6	MJ/kg	0.849	kg/kg
- Consolidation	82	MJ/rib	9.266	kg/rib
- Trimming	Incl. in cutting	-	Incl. in cutting	-
- NDI				
> A-scan	80	MJ/m^2	9.04	kg/m^2
> C-scan	80	MJ/m^2	9.04	kg/m^2
- Painting	Negligible	-	Negligible	-
- Curing/drying	117	MJ/batch	13.221	kg/batch
Operational phase	$1.72 \cdot 10^{-3}$	MJ/(kg·km)	$0.124 \cdot 10^{-3}$	kg/(kg·km)
End of life:				
- PEKK				
> Recycle	113	MJ/kg	12.769	kg/kg
> Combust	-31	MJ/kg	3.01	kg/kg
- Carbon fibre (combust)	-33.6	MJ/kg	3.76	kg/kg

3
Life Cycle Assessment (Case Study: Wing of Tomorrow)

Up until this point, the data was kept general as much as possible with the scope of being usable for any part that is to be created in the future with any of the selected materials. This chapter will now focus on the wing rib 14 within the WoT project, and will apply the general data found to the rib based on its geometry and process specifications.

3.1. Goal and scope

As it was described in chapter 1, an LCA starts with the definition of the goal and scope. Here, three main elements can be identified: the functional unit, the system boundaries and lastly the assumptions used. Starting with the functional unit, this must be a performance quantifier that describes the system being analysed as well as its objectives and the expected lifetime [49]. For the purpose of this study, the following functional unit was chosen:
”Aircraft wing structural component, responsible for giving the geometry of the wing and carrying loads both during ground and air operation of an A320 Neo aircraft, over an average lifetime of 30 years.”
This definition covers all the mentioned aspects, while simultaneously ensuring that in an eventuality of a comparison, the size of the aircraft is known.

The next step is to determine the system boundaries. This is an important step since without it the analysis would run infinitely. An example of this can be seen in Figure 3.1. Here, the sheet forming flowchart from Figure 2.2 is taken as an example. For this example, the system boundary is defined by the green rectangle. As can be seen in this figure, there are a number of elements which come behind the processes listed in this flowchart. Firstly, in the raw material production phase, the extraction of the bauxite will require the use of certain machinery. These will be powered by fuel, and will be produced using a range of materials. At their turn, the fuel and the materials must be extracted and processed, which also requires the use of machinery. Each of these are finished with a set of dotted lines. These represent the previously mentioned fact that the analysis can theoretically run on infinitely. The same can be seen for the processing stage, the operational life and the recycling stage, although these were not expanded as much for the sake of brevity. Although this is only one example, the same boundaries will be applied to all other flowcharts presented in chapter 2.
Lastly, for the assumptions of the LCA, they will be identical to those presented so far in chapter 2, and also in Appendix A, and any new assumptions will be documented in the same manner as before.

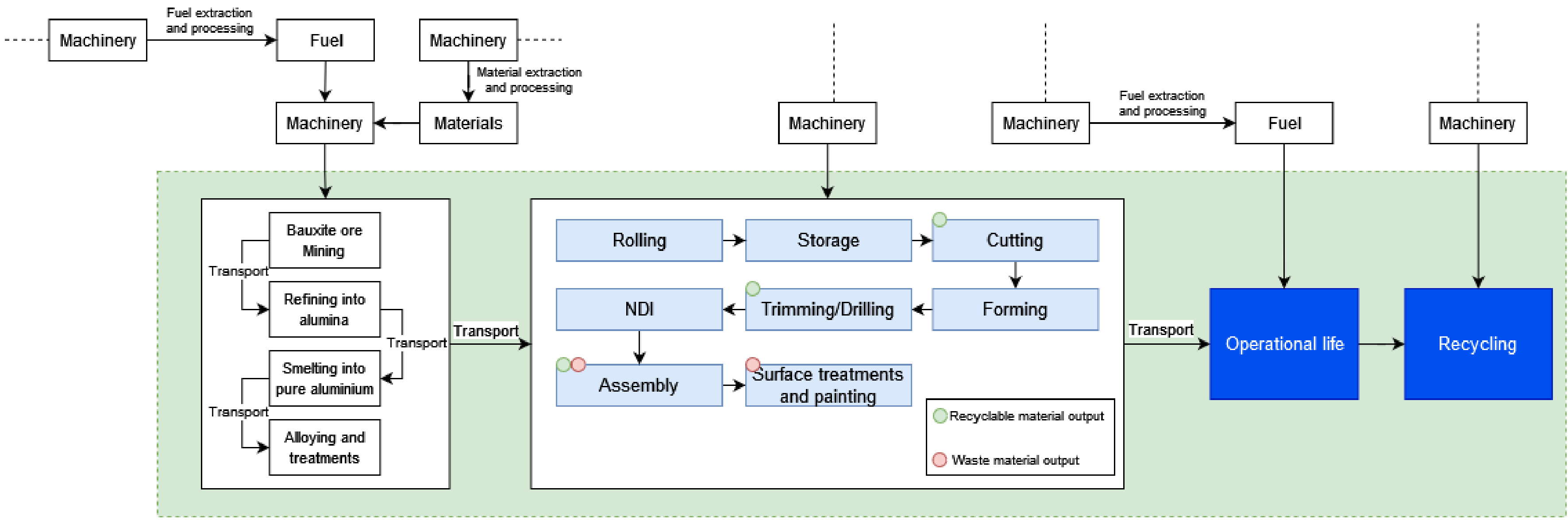

Figure 3.1: System Boundary

3.2. Inventory analysis

For this section, as it has been addressed before, a large part of the work has already been conducted via the data collection performed in chapter 2. The following subsections will apply this general data to the wing rib 14 according to its specifications.

3.2.1. Machined aluminium

The first aspect that needs to be mentioned here, is that up to the operational life, all processes must be considered starting from the finalised part and moving backwards towards raw material production. This is due to the fact that in the processing steps, material is removed, and therefore having a 1 kg of end product is not equivalent to producing 1 kg of raw material to enter the process.

Since the WoT rib has only been manufactured out of thermoplastic materials, the metal rib alternative has only a theoretical weight estimation obtained from GKN documents (020-059 TRA-TDP&TBC 1144 TP Composite Rib - 02 (CRC-R-0612)), placing it at a maximum of 3.66 kg. As mentioned above, from this number, one has to work backwards in order to determine how much material had to go into production in the first place. This can be done since the percentage of material removed at each stage is known. Let x be the starting mass of a component, and y be the end mass. By knowing the end mass and the percentage reduction in mass (say a%) it is possible to calculate the starting mass as follows:

$$
\begin{aligned}
x - \frac{a}{100} \cdot x = y \\
x = \frac{y}{1 - \frac{a}{100}}
\end{aligned}
\tag{3.1}
$$

In order to visualise this, a table was created which can be seen in Table 3.1, containing the processes and the percentage of material removed/added. In the case of the paint, it is assumed that the weight added is negligible especially since only one layer is added **[Patrick Minke, personal communication, 04.07.2022]**, and the only significant material removal occurs in the machining phase, where up to 95% of the material can be removed **[Jos Thoolen, personal communication, 13.06.2022]**. This number was verified by taking an approximate size of aluminium block for machining (0.88 m x 0.25 m x 0.2 m) based on the dimensions of the rib, multiplying the obtained volume by the density of aluminium ($2.81 \cdot 10^3$, kg/m^3 [3]). This results in a block weight of 123.64 kg, which is much higher than the 73.2 kg predicted in Table 3.1. This indicates that the size of the blocks is in practice carefully selected in order to avoid excessive waste, and additionally, it indicates that the 95% is not too high, especially since rough estimations lead to much higher numbers. Please note that for Table 3.1 as well as for all similar tables in this chapter, only a few processes are mentioned, and those are the ones which involve material removal and some arbitrarily chosen adjacent processes.

Table 3.1: Mass removed per stage - machined aluminium

Stage	%	Start mass [kg]	End mass [kg]	Removed mass [kg]
Surface treatments	0	3.66	3.66	0
NDI	0	3.66	3.66	0
Machining (coarse + fine)	95	73.2	3.66	69.54
Storage	0	73.2	73.2	0

The next set of numbers required was for the distance that the materials would have to travel before production begins. For aluminium, it was reported that the main source is Pechiney Aluminium in France, while occasionally some aluminium is being brought from Canada (about 20% of the times) **[Jos Thoolen, personal communication, 13.06.2022]**. It was assumed that for transportation from France to Hoogeveen a truck will be used, which will cover a distance of approximately 1400 km, while for the transport from Canada, a long haul flight will be required, travelling over an approximate distance of 5260 km. It will be mentioned here as well that another good alternative for transport for future studies could also be via ship.

The next step was to determine the approximate surface area of the rib. Before doing this, another assumption has to be stated, and that is that the geometry of the metal wing rib will be identical to that of the composite rib. In reality, structures created using different materials will have different geometries that accommodate for the requirements/abilities of the material. Since for this study however the metal rib has not been designed, the geometry has to be considered the same, since a full design is outside of the scope of the thesis.

Assumption
Both the aluminium and the CFRP ribs will have the same geometry.

The overall surface area was obtained from CAD drawings of the wing rib. With the feet (flanges) of the rib having a total area of 0.07 m^2, the stiffeners of 0.0338 m^2 and the plate of 0.256 m^2, the total surface area of the rib comes at 0.360 m^2. This number is to be used for the anodising processes.
For easier bookkeeping, Table 3.2 contains the numbers mentioned so far and which are required for the calculations.

Table 3.2: Entry data LCI - machined aluminium

Entry data	Value	Unit
Rib weight (Aluminium)	3.66	kg
Rib plate surface	0.256	m^2
Rib feet (flange) surface	0.07	m^2
Rib stiffener surface	0.034	m^2
Rib surface (total)	0.360	m^2
Distance FR-NL	1400	km
Distance CND-NL	5260	km

Lastly, before the final calculations were commenced, a decision was made to look at the energy usage and CO_2 emissions for multiple ribs at once, rather than one single rib at a time. This was done especially since certain processes down the line have an energy usage per batch provided, and therefore assuming that energy for one single rib will cause significant overestimations. These batch sizes were selected as follows:

- A total batch of 100 ribs in production.
- A total of roughly 30 ribs to fit in the 1 m^3 furnace selected for the NDI processes.
- A total of 100 ribs going into the paint drying furnace.

For the calculations, starting with the raw material production, and taking Al7075 as an example, it was shown in Table 2.1 that 203 MJ are required to produce one kilogram of alloy. This number was multiplied by the starting mass of aluminium of 73.2 kg found in Table 3.1 and by the total number of ribs (100). It is known however as mentioned in chapter 1, that roughly 75% of the aluminium is being recycled, which was also confirmed for the practices at GKN **[Jos Thoolen, personal communication, 13.06.2022]**. As a result, the energy is found by further multiplying this number by 0.25 (virgin aluminium fraction), and adding the remaining 75% from the production energy of recycled aluminium. It was shown in Table 2.1 that the energy for recycling Al7075 is 34.9 MJ/kg. Performing the calculation the same way as for the virgin aluminium and summing these two values up results in a total of 563091 MJ of energy required. A similar calculation was performed, this time multiplying the 22.94 kg of CO_2 per kg of alloy produced by the same weight, number of ribs and percentages, resulting in a total of 63610.8 kg of CO_2 produced. Thus, for 100 ribs:

$$\begin{aligned} E_{raw} &= 203 \cdot 73.2 \cdot 100 \cdot 0.25 + 34.9 \cdot 73.2 \cdot 100 \cdot 0.75 \\ &= 371490 + 191601 \\ &= 563091 MJ \end{aligned} \tag{3.2}$$

$$\begin{aligned} CO_{2_{raw}} &= 22.94 \cdot 73.2 \cdot 100 \cdot 0.25 + 3.94 \cdot 73.2 \cdot 100 \cdot 0.75 \\ &= 41980.2 + 21630.6 \\ &= 63610.8 kg \end{aligned} \tag{3.3}$$

Moving onto the transport stage, the 0.94 MJ/(tonne·km) visible in all summary tables for road transportation was multiplied by the distance between Pechiney Aluminium and GKN Hoogeveen, the number of ribs, the weight of the material required for making one rib (73.2 kg). Considering that as mentioned before, this accounts for 80% of the aluminium used in production, the value obtained was multiplied as well by 0.8 to find the final energy usage. Following a unit conversion from tonnes to kg, the final result for the energy consumption during this transportation came at 7706.5 MJ. CO_2 emissions are calculated by multiplying this value by the 0.072 kg/MJ as found in Table 2.1 with 554.9 kg being obtained (for 100 ribs).

$$E_{road} = \frac{0.94 \cdot 1400 \cdot 100 \cdot 73.2 \cdot 0.8}{1000} \quad (3.4)$$
$$= 7706.5MJ$$
$$CO_{2_{road}} = 0.072 \cdot 7706.496 \quad (3.5)$$
$$= 554.9kg$$

The remaining 20% were calculated in the same way, but this time taking the long haul energy of 6.5 MJ/(tonne·km), and the distance between Quebec and Amsterdam (assuming flights will arrive at Schiphol Airport). The calculated energy and CO_2 production for this were 50054.2 MJ and 3603.9 kg respectively. From Schiphol airport to GKN Hoogeveen, another transportation on the road would normally be required, however seeing the difference in energy requirements between the road transport over 1400 km and air transport over 5200km, an additional small distance of 150 km by road was considered negligible and therefore not included in the calculation.

$$E_{air} = \frac{6.5 \cdot 5260 \cdot 100 \cdot 73.2 \cdot 0.2}{1000} \quad (3.6)$$
$$= 50054.2MJ$$
$$CO_{2_{air}} = 0.072 \cdot 50054.16 \quad (3.7)$$
$$= 3603.9kg$$

The next step was to calculate the machining energy within the manufacturing stage. Here, similarly to what was seen for the transport stage, the energy has to be divided between coarse and fine machining, knowing that roughly 70% of the material is removed using coarse machining **[Jos Thoolen, personal communication, 13.06.2022]**. Using once again the specific values from Table 2.1, and multiplying them this time by the amount of material removed during the machining processes (69.54 kg), the number of ribs and by the correct percentage per process, the energies and CO_2 values for coarse and fine machining are found at 9540.9 MJ, 1075.8 kg, and 30875.8 MJ, 3488.1 kg respectively.

$$E_{coarse} = 1.96 \cdot 69.54 \cdot 100 \cdot 0.7 \quad (3.8)$$
$$= 9540.9MJ$$
$$CO_{2_{coarse}} = 0.221 \cdot 69.54 \cdot 100 \cdot 0.7 \quad (3.9)$$
$$= 1075.8kg$$
$$E_{fine} = 14.8 \cdot 69.54 \cdot 100 \cdot 0.3 \quad (3.10)$$
$$= 30875.8MJ$$
$$CO_{2_{fine}} = 1.672 \cdot 69.54 \cdot 100 \cdot 0.3 \quad (3.11)$$
$$= 3488.1kg$$

Following machining is the NDI stage, where the two energy consumers identified were the preparation phase and the drying of the parts prior to die penetrant inspection. For the preparation, the energy was found in chapter 2 as 194 MJ/batch. For this example, it is assumed that 30 parts can be degreased simultaneously. This comes from the assumptions made during data collection, only a maximum of 30 ribs could go in the oven at once (size limitations). As a result of this, it was assumed that the preparation would take a similar number of parts.

Assumption

NDI preparation (degreasing) for metals takes the same amount of parts at once as the drying stage prior to the inspection.

In order to account for the smaller number of ribs going in the process at once, the energy can be multiplied by the ratio between the total number of parts to be produced and the number of parts going in the process at once (in this case, the ratio being 100/30). The energy for this comes at 646.7 MJ, with 73.1 kg of CO_2 produced. For the drying part, the same procedure can be applied, resulting in 92.3 MJ of energy with 10.4 kg of CO_2 produced.

$$E_{preparation} = 194 \cdot \frac{100}{30} = 646.7MJ \tag{3.12}$$

$$CO2_{preparation} = 21.922 \cdot \frac{100}{30} = 73.1kg \tag{3.13}$$

$$E_{oven} = 27.7 \cdot \frac{100}{30} = 92.3MJ \tag{3.14}$$

$$CO2_{oven} = 3.13 \cdot \frac{100}{30} = 10.4kg \tag{3.15}$$

For anodising, the specific energy was found as a function of the surface which has to be anodised. Multiplying the 1.44 MJ/m^2 value found in Table 2.1 by the surface area of the rib from Table 3.2 and the total number of ribs, the energy is found at 51.8 MJ and the CO_2 amount at 5.9 kg.

$$E_{anodising} = 1.44 \cdot 0.360 \cdot 100 = 51.8MJ \tag{3.16}$$

$$CO2_{anodising} = 0.163 \cdot 0.360 \cdot 100 = 5.9kg \tag{3.17}$$

Next, looking at curing/drying energy for the paint, the same specific energy/batch was found in chapter 2. The ovens for curing paint however are large, meaning that the 100 parts could go in all at the same time. The same method as for NDI is applied for this, however this time the ratio is at $\frac{100}{100}$, or 1. This results in 117 MJ of energy and 13.2 kg of CO_2.

$$E_{drying} = 117 \cdot \frac{100}{100} = 117MJ \tag{3.18}$$

$$CO2_{drying} = 13.221 \cdot \frac{100}{100} = 13.2kg \tag{3.19}$$

In the operational stage, the energy required and the CO_2 emissions were given as a function of the distance travelled and the weight of the part (similarly to what was seen in the transport stage). Here it was necessary to make another assumption regarding the life of an aircraft. It is assumed that the average lifetime of the aircraft (this including the ribs) will be of approximately 30 years, during which an estimate of 84490560 km will be travelled [14]. Multiplying the specific energy (from Table 2.1 by this distance, the weight of a rib and the total number of ribs considered, the energy is found to be 53188497.3 MJ, and the CO_2 amount 3834519.6 kg.

$$E_{operational} = 0.00172 \cdot 84490560 \cdot 3.66 \cdot 100 = 53188497.3MJ \tag{3.20}$$

$$CO2_{operational} = 0.000124 \cdot 84490560 \cdot 3.66 \cdot 100 = 3834519.6kg \tag{3.21}$$

Lastly, for the recycling phase, the energy found in Table 2.1 was 34.9 MJ/kg. The total amount of aluminium that has to be recycled now includes the ribs and also the material which was machined away in production, since it was assumed previously that all the aluminium can be recycled. As a result, the specific energy has to be multiplied by the total amount of aluminium that entered the process for one rib (73.2 kg) and then by the number of ribs considered (100), resulting in 255468 MJ of energy and 28840.8 kg of CO_2. A final aspect that needs to be considered here is that a part of the recycling energy was used for the primary material production. In other words, a part of the energy obtained from here will be part of the life cycle assessment of the next part being manufactured, and therefore by not subtracting that number, the total energy consumption and CO_2 emissions are overestimated. Overall, 191601 MJ and 21630.6 kg of CO_2-eq have to be removed.

$$\begin{aligned} E_{recycling} &= 34.9 \cdot 73.2 \cdot 100 - 191601 \\ &= 63867MJ \end{aligned} \tag{3.22}$$

$$\begin{aligned} CO2_{recycling} &= 3.94 \cdot 73.2 \cdot 100 - 21630.6 \\ &= 7210.2kg \end{aligned} \tag{3.23}$$

This concludes the calculations for the machined Al7075 T73 alloy. The same methodology is then applied for the Al7050 T7451, and the results can be seen in Figure 3.2. Additionally, bar charts of the distribution of energy consumption per life stage and also CO_2 emissions for 100 ribs for each of these stages can be seen in Figure 3.3 with the operational phase excluded, and Figure 3.4 with it included.

Energy and CO2	Specific								Total								
	Al 7075				Al 7050				Al 7075				Al 7050				
	Energy	Unit	CO2	Unit	Energy	Unit	CO2	Unit	Energy	Unit	CO2	Unit	Energy	Unit	CO2	Unit	%
Raw material production																	
____Virgin	203	MJ/kg	22.94	kg/kg	201	MJ/kg	22.71	kg/kg	371490.0	MJ	41980.2	kg	367830.0	MJ	41559.3	kg	25.00
____Recycled	34.9	MJ/kg	3.94	kg/kg	34.6	MJ/kg	3.91	kg/kg	191601.0	MJ	21630.6	kg	189954.0	MJ	21465.9	kg	75.00
Transport																	
____Road	0.94	MJ/(t*km)	0.072	kg/MJ	0.94	MJ/(t*km)	0.072	kg/MJ	7706.5	MJ	554.9	kg	7706.5	MJ	554.9	kg	80.00
____Air (LH)	6.5	MJ/(t*km)	0.072	kg/MJ	6.5	MJ/(t*km)	0.072	kg/MJ	50054.2	MJ	3603.9	kg	50054.2	MJ	3603.9	kg	20.00
Storage	0	N/A	0	N/A	0	N/A	0	N/A	0.0	N/A	0.0	N/A	0.0	N/A	0.0	N/A	100.00
Machining																	
____Coarse	1.96	MJ/kg rem	0.221	kg/kg rem	2.12	MJ/kg rem	0.24	kg/kg rem	9540.9	MJ	1075.8	kg	10319.7	MJ	1168.3	kg	70.00
____Fine	14.8	MJ/kg rem	1.672	kg/kg rem	16.5	MJ/kg rem	1.865	kg/kg rem	30875.8	MJ	3488.1	kg	34422.3	MJ	3890.8	kg	30.00
NDI																	
____Prep	194	MJ/batch	21.922	kg/batch	194	MJ/batch	21.922	kg/batch	646.7	MJ	73.1	kg	646.7	MJ	73.1	kg	100.00
____Oven	30.8	MJ/batch	3.48	kg/batch	30.8	MJ/batch	3.48	kg/batch	102.7	MJ	11.6	kg	102.7	MJ	11.6	kg	100.00
Anodising	1.44	MJ/m2	0.163	kg/m2	1.44	MJ/m2	0.163	kg/m2	51.8	MJ	5.9	kg	51.8	MJ	5.9	kg	100.00
Painting	0	N/A	0	N/A	0	N/A	0	N/A	0.0	N/A	0.0	N/A	0.0	N/A	0.0	N/A	100.00
Curing/drying	117	MJ/batch	13.221	kg/batch	117	MJ/batch	13.221	kg/batch	117.0	MJ	13.2	kg	117.0	MJ	13.2	kg	100.00
Operational phase	0.00172	MJ/(kg*km)	0.000124	kg/(kg*km)	0.00172	MJ/(kg*km)	0.000124	kg/(kg*km)	53188497.3	MJ	3834519.6	kg	53188497.3	MJ	3834519.6	kg	100.00
Recycling	34.9	MJ/kg	3.94	kg/kg	34.6	MJ/kg	3.91	kg/kg	63867.0	MJ	7210.2	kg	63318.0	MJ	7155.3	kg	100.00

Totals for 100 ribs	**5.3915E+07**	**MJ**	3.9142E+06	**kg**	**5.3913E+07**	**MJ**	**3.9140E+06**	**kg**
Of which:	Al7075 (machined)		Al7075 (machined)		Al7050 (machined)		Al7050 (machined)	
Raw material	5.6309E+05	MJ	6.3611E+04	kg	5.5778E+05	MJ	6.3025E+04	kg
Transport	5.7761E+04	MJ	4.1588E+03	kg	5.7761E+04	MJ	4.1588E+03	kg
Production	4.1335E+04	MJ	4.6677E+03	kg	4.5660E+04	MJ	5.1628E+03	kg
Operational	5.3188E+07	MJ	3.8345E+06	kg	5.3188E+07	MJ	3.8345E+06	kg
Recycling	6.3867E+04	MJ	7.2102E+03	kg	6.3318E+04	MJ	7.1553E+03	kg

Figure 3.2: Energy and CO_2 calculations summary for machined aluminium alloys

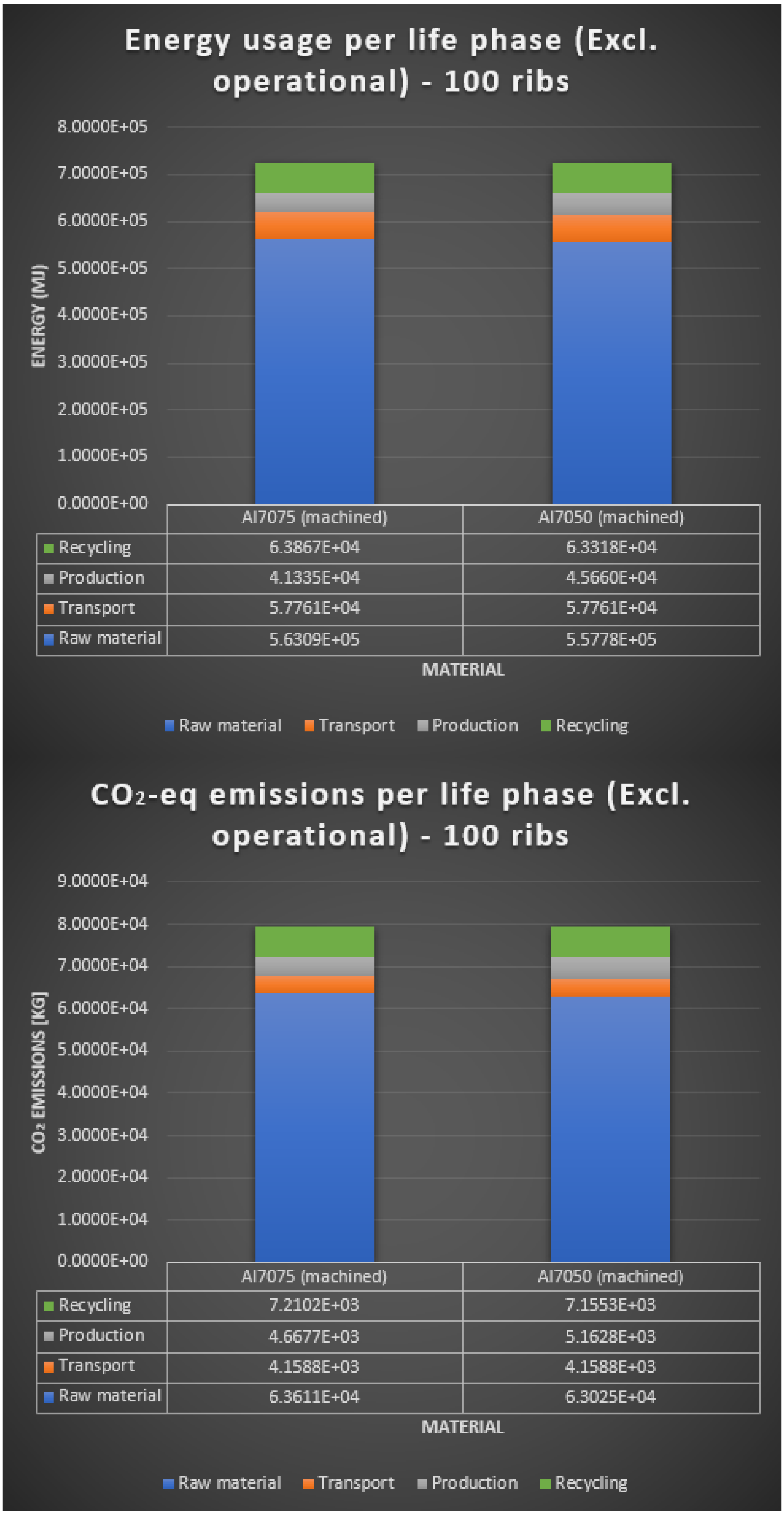

Figure 3.3: Machined aluminium energy and CO_2 per life stage charts (excluding the operational phase).

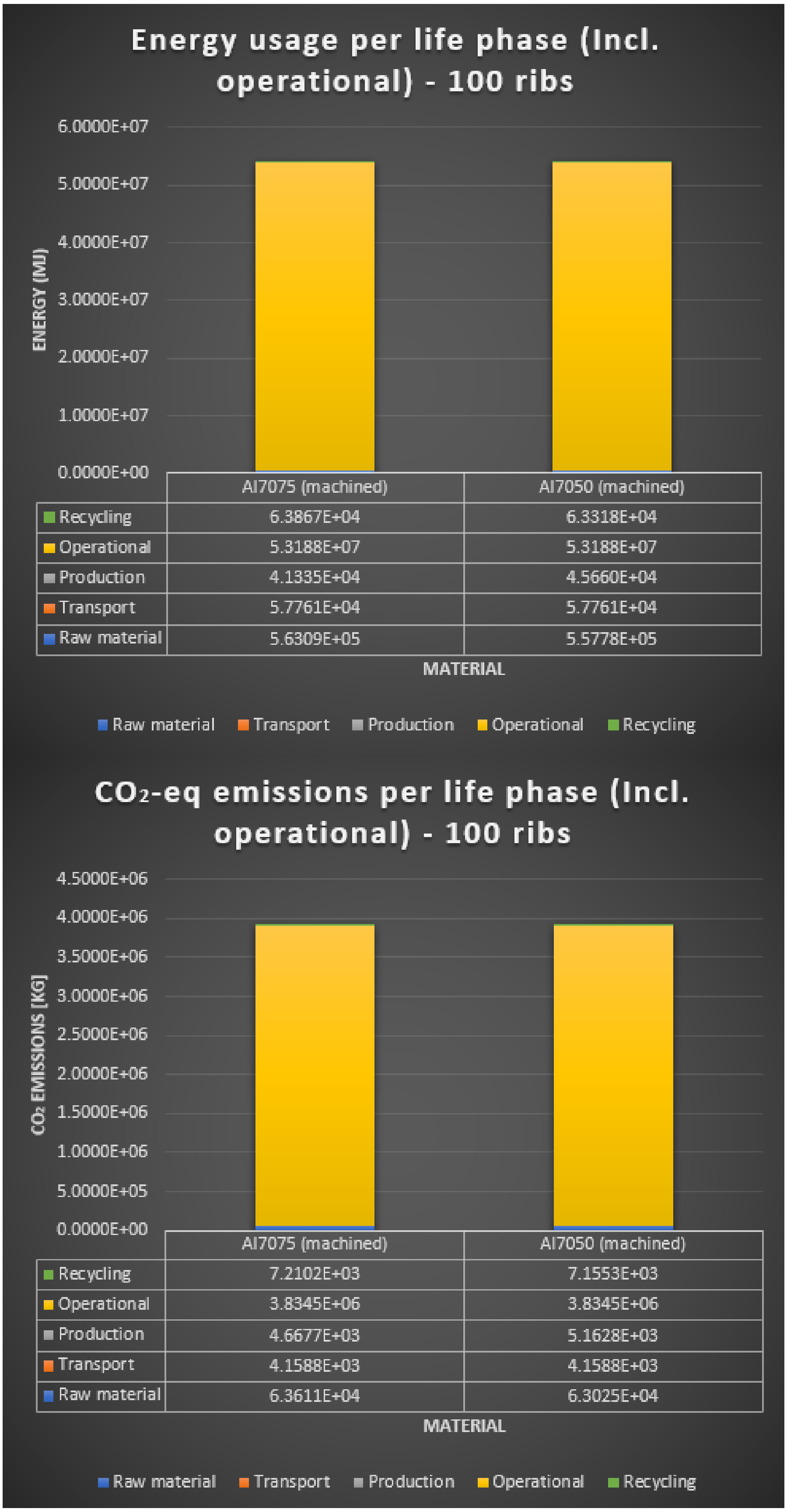

Figure 3.4: Machined aluminium energy and CO_2 per life stage charts (including the operational phase)

3.2.2. Aluminium sheet metal forming

For sheet forming, the approach remains largely the same. Once again, the calculations start with considering the geometry of the rib, the surface areas and the material removed/added during the processing steps. This time, since sheet forming has to be used for a T-shaped cross-section, this can not be done in one step, but two symmetrical rib halves have to be created and bonded back-to-back. The wingbox cross-section that rib 14 fills has a length of 0.88 m and a width of 0.23 m [6]. This would require an initial metal plate capable of fitting two rectangles of these dimensions. In order to accomplish this and have a small margin for when the actual rib geometry is cut out, a plate of 1 m by 0.7 m was chosen. From the two rectangles the geometry of the rib has to be cut out, including the inside cutouts. What must be found is the amount of material that is removed (similar to what was done for machining). One additional comment here is that for the design of such a rib, stiffening elements will still be required, however, for the calculations in this chapter these are not taken into account. This is due to the fact that the exact dimensions are not known (non-existent design), and therefore are assumed negligible compared to the processing for the rib itself.

Assumption

For the sheet formed rib, the stiffener design is unknown. Processing energy assumed negligible.

If one were to unfold the feet of the rib, the surface area obtained would be that of the plate (web) and half the base of the flanges (minus the thickness of the plate). Using the CAD drawings of the wing rib, this was estimated as:

$$\begin{aligned} A_{rib} &= 0.128 + 0.001 + 0.005 + 0.004 + 0.005 \\ &= 0.143 m^2 \end{aligned} \tag{3.24}$$

Considering now that the starting sheet had a surface area of 0.7 m^2, that would mean that only 0.286 m^2 are used, out of which the remaining are cut and recycled. This would equate to 40.9%. Just like for machining, a table with the material removed was created in Table 3.3. For this particular material flow it was assumed that there is no added mass in the painting step just like in the case of the machined aluminium, and additionally it was considered that the weight added by the adhesive for assembly is also negligible. This is a limitation since this weight may be necessary, however as mentioned before, this wing rib was never manufactured out of aluminium and therefore this design parameter (adhesive thickness and type) is missing.

Table 3.3: Mass removed per stage - sheet formed aluminium

Stage	%	Start mass [kg]	End mass [kg]	Removed mass [kg]
Surface treatments	0	3.66	3.66	0
Assembly	0	3.66	3.66	0
NDI	0	3.66	3.66	0
Trimming	0	3.66	3.66	0
Forming	0	3.66	3.66	0
Cutting	59.1	8.96	3.66	5.3
Storage	0	8.96	8.96	0
Rolling	0	8.96	8.96	0

All other parameters from Table 3.2 remain the same for further calculations. Starting with the calculations and using once again the Al7075 T73 alloy as an example, the raw material production as well as the transport energies and CO_2 emissions are calculated identically to what was seen in the previous subsection for machined aluminium.

$$\begin{aligned} E_{raw} &= 203 \cdot 8.96 \cdot 100 \cdot 0.25 + 34.9 \cdot 8.96 \cdot 100 \cdot 0.75 \\ &= 45462.2219 + 23447.7568 \\ &= 68910.0MJ \end{aligned} \tag{3.25}$$

$$\begin{aligned} CO2_{raw} &= 22.94 \cdot 8.96 \cdot 100 \cdot 0.25 + 3.91 \cdot 8.96 \cdot 100 \cdot 0.75 \\ &= 5137.4550 + 2647.1107 \\ &= 7784.7kg \end{aligned} \tag{3.26}$$

$$\begin{aligned} E_{road} &= \frac{0.94 \cdot 1400 \cdot 100 \cdot 8.96 \cdot 0.8}{1000} \\ &= 943.1MJ \end{aligned} \tag{3.27}$$

$$\begin{aligned} CO2_{road} &= 0.072 \cdot 943.11MJ \\ &= 67.9kg \end{aligned} \tag{3.28}$$

$$\begin{aligned} E_{air} &= \frac{6.5 \cdot 5260 \cdot 100 \cdot 8.96 \cdot 0.2}{1000} \\ &= 6125.5MJ \end{aligned} \tag{3.29}$$

$$\begin{aligned} CO2_{air} &= 0.072 \cdot 6125.53MJ \\ &= 441kg \end{aligned} \tag{3.30}$$

Moving into the processing phase, some changes appear in the material flow. First is the presence of rolling. Rolling can be done as seen in chapter 2 with or without heating up the part. For the current analysis, cold rolling was chosen. The numbers of hot rolling are computed as well, however in the determination of the total energy at the end, only one of the two processes has to be selected and added to the total value (in this case, cold rolling).

Assumption

For the sheet formed rib, cold rolling is used.

The specific energies for hot and cold rolling were 2.232 MJ/kg and 2.304 MJ/kg respectively. Thus, multiplying these values by the weight of the sheet going into the process (before cutting), one obtains 1999.4 MJ and 2063.9 MJ. Similarly, using the specific values for CO_2 emissions of 0.26 kg/kg and 0.252 kg/kg, one obtains a total of 225.7 kg and 232.9 kg.

$$\begin{aligned} E_{rolling(hot)} &= 2.232 \cdot 8.96 \cdot 100 \\ &= 1999.4MJ \end{aligned} \tag{3.31}$$

$$\begin{aligned} CO2_{rolling(hot)} &= 0.252 \cdot 8.96 \cdot 100 \\ &= 225.7kg \end{aligned} \tag{3.32}$$

$$\begin{aligned} E_{rolling(cold)} &= 2.304 \cdot 8.96 \cdot 100 \\ &= 2063.9MJ \end{aligned} \tag{3.33}$$

$$\begin{aligned} CO2_{rolling(cold)} &= 0.260 \cdot 8.96 \cdot 100 \\ &= 232.9kg \end{aligned} \tag{3.34}$$

Cutting is the next process in the flow. For this, another assumption was required, and that is regarding the time required to cut the ribs out of the initial plates, and also to make the cutouts into the ribs. Additionally, this process was clustered as well with any trimming that may be required at the end of the forming processes. For the purpose of this analysis, the time required was approximated as 30 minutes per rib profile. The cutting type which will be used for this analysis is mechanical cutting as opposed to plasma cutting. As a result, the energy is negligible.

Assumption

Cutting for all ribs is done with mechanical cutting and takes roughly 30 minutes per part, and that includes the trimming required after the main processing steps.

The energy required for cutting using plasma can still be calculated however, in case it will be needed for other processes. For this, the specific energy of 172 MJ/h from Table 2.3 was multiplied by the time estimated above of 0.5 hours, by the number of ribs (100) and lastly by 2, since each of the ribs will require two halves to be cut. This results in 17280 MJ of energy, and using the same process for CO_2 as well one obtains 1952.6 kg.

$$E_{cutting} = 172.8 \cdot 0.5 \cdot 100 \cdot 2 \tag{3.35}$$
$$= 17280MJ$$
$$CO_{2_{cutting}} = 19.526 \cdot 0.5 \cdot 100 \cdot 2 \tag{3.36}$$
$$= 1952.6kg$$

For NDI, in the case of sheet formed parts, the inspection can be done visually, and therefore no energy is required (and no CO_2 emissions are present) **[Marc Koetsier, personal communication, 26.08.2022]**.

Next, as per the previous assumptions, the overall geometry of the rib remains the same regardless of material or process flow chosen, and therefore the surface does not change. As a result, the anodising and painting energies, with the calculations shown from Equation 3.16 until Equation 3.19 do not change.

The last step of the processing stage is the assembly. Since it is assumed that the ribs will be assembled using adhesive bonding, the largest energy usage will come from the curing of the adhesive. It was assumed previously in chapter 2 that a similar oven to that used in NDI will be used for this process as well, therefore the number of ribs that will fit in it is again 30. Multiplying the specific energy of 92.184 MJ/batch by the ratio between the total batch size and the number of ribs going in the oven at once, one obtains a total of 307.3 MJ of energy and similarly 34.7 kg of CO_2.

$$E_{assembly} = 92.184 \cdot \frac{100}{30} \tag{3.37}$$
$$= 307.3MJ$$
$$CO_{2_{assembly}} = 10.41 \cdot \frac{100}{30} \tag{3.38}$$
$$= 34.7kg$$

Moving into the operational phase, once again the numbers do not change since the material is the same, and therefore so is the weight of the rib. The process for calculating the energy and CO_2 emissions was shown in Equation 3.20 and Equation 3.21 respectively.

The last stage is recycling. Here, the method for calculating the energy and CO_2 remain the same, however due to the different weights of aluminium required, the end values are different. Once again, for calculating the energy, the specific energy of 34.9 MJ/kg is multiplied by the total amount of aluminium entering production for one rib, and then by the number of ribs. This results in an energy consumption of 31263.7 MJ and 3529.5 kg of CO_2.

$$E_{recycling} = 34.9 \cdot 8.96 \cdot 100 \tag{3.39}$$
$$= 31263.7MJ$$
$$CO_{2_{recycling}} = 3.94 \cdot 8.96 \cdot 100 \tag{3.40}$$
$$= 3529.5kg$$

The same process is applied as well for the other alloy, Al7050 T7451, and all the results for 100 ribs are shown in Figure 3.5 with the bar charts shown as well in Figure 3.6 and Figure 3.7.

Energy and CO2	Specific								Total								
	Al 7075				Al 7050				Al 7075				Al 7050				
	Energy	Unit	CO2	Unit	Energy	Unit	CO2	Unit	Energy	Unit	CO2	Unit	Energy	Unit	CO2	Unit	%
Raw material production																	
_____Virgin	203	MJ/kg	22.94	kg/kg	201	MJ/kg	22.71	kg/kg	45462.2	MJ	5137.5	kg	45014.3	MJ	5085.9	kg	25.00
_____Recycled	34.9	MJ/kg	3.94	kg/kg	34.6	MJ/kg	3.91	kg/kg	23447.8	MJ	2647.1	kg	23246.2	MJ	2627.0	kg	75.00
Transport																	
_____Road	0.94	MJ/(t*km)	0.072	kg/MJ	0.94	MJ/(t*km)	0.072	kg/MJ	943.1	MJ	67.9	kg	943.1	MJ	67.9	kg	80.00
_____Air (LH)	6.5	MJ/(t*km)	0.072	kg/MJ	6.5	MJ/(t*km)	0.072	kg/MJ	6125.5	MJ	441.0	kg	6125.5	MJ	441.0	kg	20.00
Storage	0	N/A	0	N/A	0	N/A	0	N/A	0.0	N/A	0.0	N/A	0.0	N/A	0.0	N/A	100.00
Rolling																	
____Hot	2.232	MJ/kg	0.252	kg/kg	2.232	MJ/kg	0.252	kg/kg	1999.4	MJ	225.7	kg	1999.4	MJ	225.7	kg	0.00
____Cold	2.304	MJ/kg	0.26	kg/kg	2.304	MJ/kg	0.26	kg/kg	2063.9	MJ	232.9	kg	2063.9	MJ	232.9	kg	100.00
Cutting																	
___Plasma	172.8	MJ/h	19.526	kg/hour	172.8	MJ/h	19.526	kg/hour	17280.0	MJ	1952.6	kg	17280.0	MJ	1952.6	kg	0.00
___Mechanical	0	N/A	0	N/A	0	N/A	0	N/A	0.0	N/A	0.0	N/A	0.0	N/A	0.0	N/A	100.00
Forming	0	N/A	0	N/A	0	N/A	0	N/A	0.0	N/A	0.0	N/A	0.0	N/A	0.0	N/A	100.00
NDI																	
____Prep	194	MJ/batch	21.922	kg/batch	194	MJ/batch	21.922	kg/batch	0.0	MJ	0.0	kg	0.0	MJ	0.0	kg	100.00
____Oven	27.7	MJ/batch	3.051	kg/batch	27	MJ/batch	3.051	kg/batch	0.0	MJ	0.0	kg	0.0	MJ	0.0	kg	100.00
Anodising	1.44	MJ/m2	0.163	kg/m2	1.44	MJ/m2	0.163	kg/m2	51.8	MJ	5.9	kg	51.8	MJ	5.9	kg	100.00
Painting	0	N/A	0	N/A	0	N/A	0	N/A	0.0	N/A	0.0	N/A	0.0	N/A	0.0	N/A	100.00
Curing/drying	117	MJ/batch	13.221	kg/batch	117	MJ/batch	13.221	kg/batch	117.0	MJ	13.2	kg	117.0	MJ	13.2	kg	100.00
Assembly	92.184	MJ/batch	10.41	kg/batch	92.184	MJ/batch	10.41	kg/batch	307.3	MJ	34.7	kg	307.3	MJ	34.7	kg	100.00
Operational phase	0.00172	MJ/(kg*km)	0.000124	kg/(kg*km)	0.00172	MJ/(kg*km)	0.000124	kg/(kg*km)	53188497.3	MJ	3834519.6	kg	53188497.3	MJ	3834519.6	kg	100.00
Recycling	34.9	MJ/kg	3.94	kg/kg	34.6	MJ/kg	3.91	kg/kg	7815.9	MJ	882.4	kg	7748.7	MJ	875.7	kg	100.00

Totals for 100 ribs	**5.3277E+07**	**MJ**	3.8442E+06	**kg**	**5.3276E+07**	**MJ**	**3.8441E+06**	**kg**
Of which:	Al7075 (formed)		Al7075 (formed)		Al7050 (formed)		Al7050 (formed)	
Raw material	6.8910E+04	MJ	7.7846E+03	kg	6.8261E+04	MJ	7.7129E+03	kg
Transport	7.0686E+03	MJ	5.0894E+02	kg	7.0686E+03	MJ	5.0894E+02	kg
Production	2.5400E+03	MJ	2.8670E+02	kg	2.5400E+03	MJ	2.8670E+02	kg
Operational	5.3188E+07	MJ	3.8345E+06	kg	5.3188E+07	MJ	3.8345E+06	kg
Recycling	7.8159E+03	MJ	8.8237E+02	kg	7.7487E+03	MJ	8.7565E+02	kg

Figure 3.5: Energy and CO_2 calculations summary for sheet formed aluminium alloys

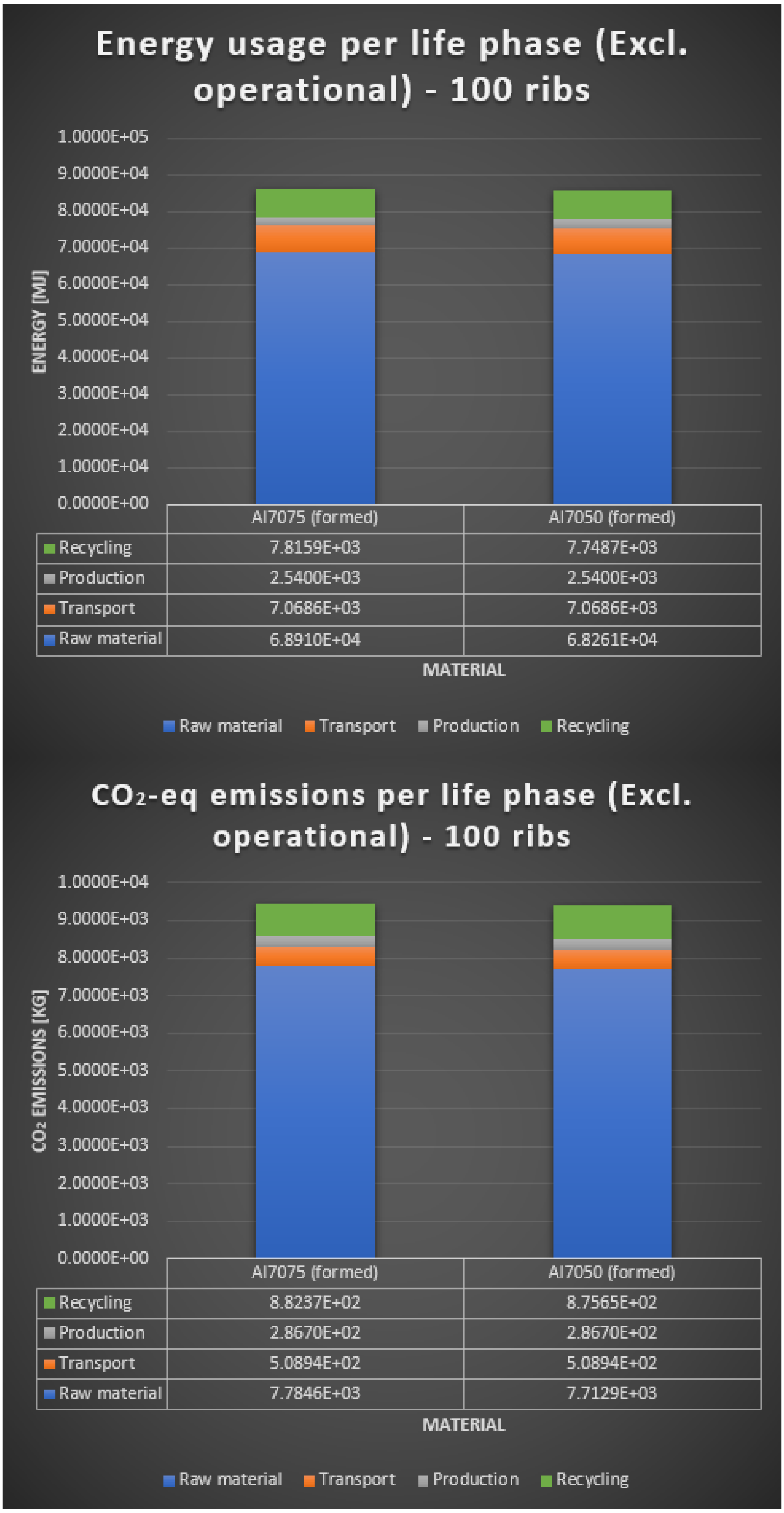

Figure 3.6: Sheet formed aluminium energy and CO_2 per life stage charts (excluding the operational phase)

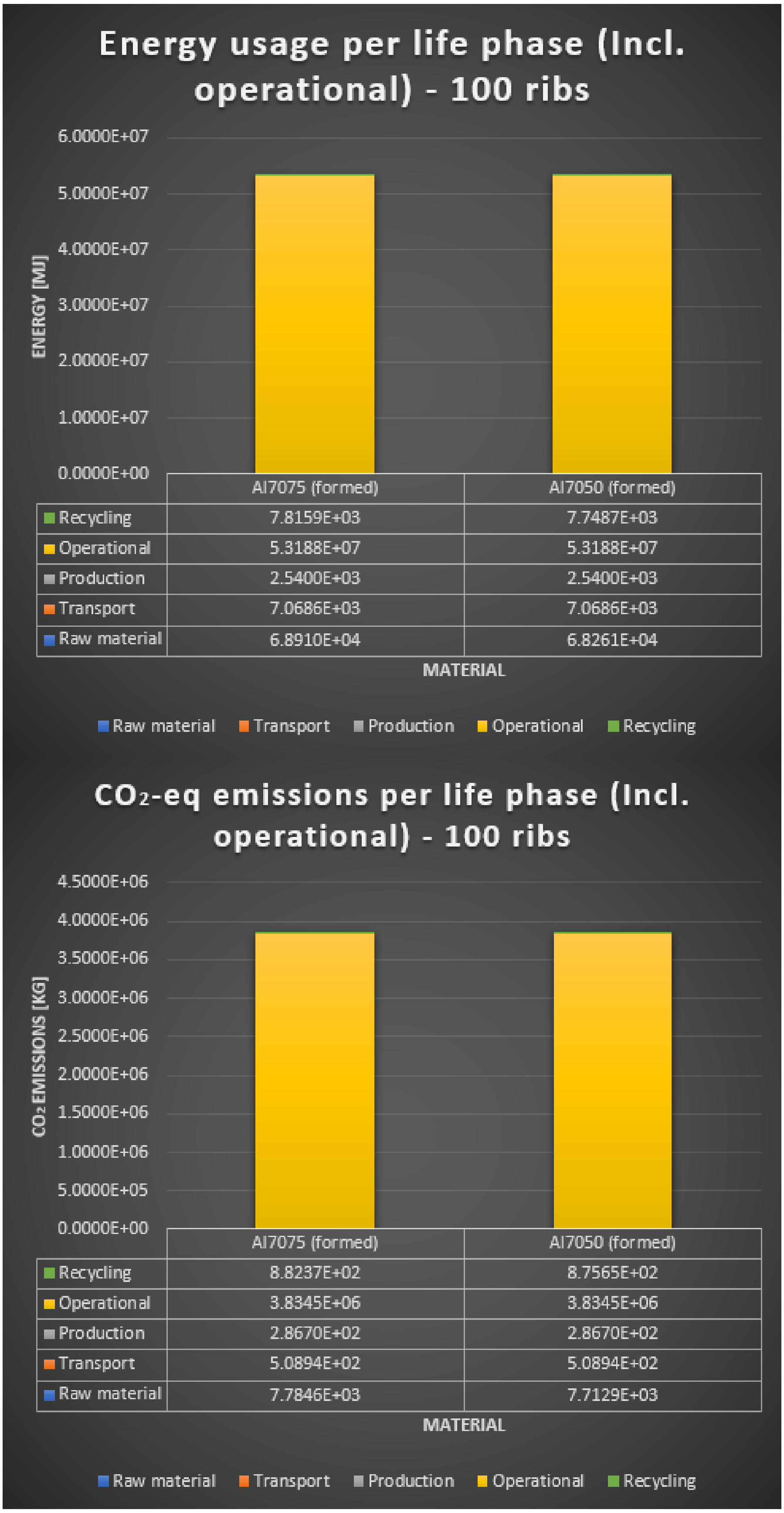

Figure 3.7: Sheet formed aluminium energy and CO_2 per life stage charts (including the operational phase)

3.2.3. Thermoset Epoxy-CFRP prepreg composite

Before starting the analysis on the composite materials, an assumption has to be made about the weights of the components. Considering that the thermoset version of this rib was not built either, the exact weight of that design is unknown. In the absence of this information, it will be assumed that all composite ribs (both thermoset prepreg and thermoset RTM, and the thermoplastic one) will have the same weight.

Assumption

All composite versions of the wing rib have the same weight.

Similarly to what was done for aluminium, Table 3.4 presents the entry data for the composites. As can be seen here, the supplier of the materials resides in Stamford, Connecticut, USA for the thermosets and Houston, Texas, USA for the thermoplastics. Additionally, the batch sizes mentioned for aluminium remain applicable for composites too.

Table 3.4: Entry data LCI - composites

Entry data	Value	Unit
Rib weight (CFRP)	2.1	kg
Rib plate surface	0.256	m^2
Rib feet surface	0.07	m^2
Rib stiffener surface	0.034	m^2
Rib surface (total)	0.360	m^2
Distance CT-NL (TS)	5700	km
Distance TX-NL (TP)	8070	km

For composites, material will be cut throughout the processes too, and therefore the weight of material in to weight of material out ratio is not 1 here either. Table 3.5 shows the material removal similarly to what was done previously for aluminium.

Table 3.5: Mass removed per stage - Epoxy CFRP Prepreg

Stage	%	Start mass [kg]	End mass [kg]	Removed mass [kg]
Surface treatments	0	2.1	2.1	0
NDI	0	2.1	2.1	0
Trimming	0	2.1	2.1	0
Autoclave	0	2.1	2.1	0
Layup	0	2.1	2.1	0
Cutting	40	3.5	2.1	1.4
Thawing	0	3.5	3.5	0
Cooled storage	0	3.5	3.5	0

For this table, the percentage removal was initially calculated similarly to what was done for the sheet formed aluminium. The size of a starting prepreg sheet was estimated at 0.3 m^2 based on the dimensions of the rib, and the total surface area after the cutouts are made as well was taken as 0.143 m^2 again. This indicated a removal of 52% of the material. This can of course be improved by reducing the margins around the material (which can be done by better nesting of the shapes on the sheet by a computer algorithm). According to data obtained from GKN Bristol, a maximum of 40% is cut away for composites, this including the trimming after the process **[Wesley McNulty, personal communication, 22.06.2022]**. As a result this number was used instead of the calculated 52%.

The first step was once again to calculate the raw material production energy and CO_2 emissions.

$$E_{raw} = 723 \cdot 3.5 \cdot 100 \tag{3.41}$$
$$= 253050MJ$$
$$CO_{2_{raw}} = 22.94 \cdot 3.5 \cdot 100 \tag{3.42}$$
$$= 35680.05kg$$

Since this time the prepreg comes from one source only, 100% of the energy will be attributed to the travel from this source. Despite working with thermoset composites, cooled transport was not considered in this case. The reasoning behind this is that as opposed to cooled transport by truck, where diesel engines are used to keep the contents cold (see chapter 2), for air transport this is more difficult to achieve. As a result, typically insulating boxes are used and also possibly dry ice in order to keep the cargo at the desired temperature [43]. These require no energy with the exception of the production of the ice and the containers, however these fall outside the boundaries set for this study and therefore are not included in the calculations.

$$E_{air} = \frac{6.5 \cdot 5700 \cdot 100 \cdot 3.5}{1000} \tag{3.43}$$
$$= 12967.5MJ$$
$$CO_{2_{air}} = 0.072 \cdot 1297.5MJ \tag{3.44}$$
$$= 933.66kg$$

While cooled transport does not have to be considered, cooled storage does. For reasons mentioned in chapter 2, the estimated refrigeration time is of 18 months. The numbers for energy consumption were calculated based on a case study of an inside ski slope in the United Arab Emirates, and in order to check whether this is also applicable in the Netherlands (considering the climate difference), research was conducted into the average temperatures in the Netherlands. For the Emirates, considering the outside temperature compared to the inside temperature for the ski slope, the average ΔT which is the important parameter for the calculations is of approximately 30°C. Using data from weather websites [13], a table with average monthly temperatures in the Netherlands was created. This table can be seen in Table 3.6. These values were taken for the north of the Netherlands (Groningen, which is close to Hoogeveen), such that they are more accurate considering where the materials will be stored.

Table 3.6: Average monthly temperature in the north of the Netherlands

	Monthly avg. Temp (°C)	**ΔT**
Jan	5	23
Feb	6	24
Mar	9	27
Apr	13	31
May	17	35
Jun	20	38
Jul	22	40
Aug	21	39
Sep	18	36
Oct	14	32
Nov	9	27
Dec	6	24
Average ΔT		**31**

As can be seen from this table, the average ΔT over the year is of approximately 31°C, which means the energy calculations done for the ski slopes in the Emirates will be applicable for the storage in the Netherlands as well since the heat energy that has to be removed is the same. The last step for calculation of the storage energy was to determine the volume that needs to be cooled for the wings considered. The storage size in Hoogeveen was approximated previously at 3500 m^3 however this is the total storage which is used for a large number of materials, not only for the materials for 100 ribs considered in this study. It has been shown previously in chapter 2 that the energy scales down linearly with the size of the storage room, as a result the only estimation that has to be made is for the volume of the materials for the 100 ribs. The volume that one rib will take up in storage was assumed to be that of a parallelepiped, with dimensions 0.23 m x 0.88 m x 0.1 m, which are the maximum dimensions of the rib. Since the material that enters the process is in fact larger than that coming out of the processing stage, the ratio of material in to material out also has to be considered for this calculation. The volume is therefore calculated as:

$$\begin{aligned} V_{storage} &= 0.1 \cdot 0.23 \cdot 0.88 \cdot \frac{3.5}{2.1} \cdot 100 \\ &= 3.4m^3 \end{aligned} \tag{3.45}$$

Additionally this method was also used to verify the previously made assumption that 30 ribs would fit in the 1 m^3 oven used for NDI. These ribs would take up a volume of roughly 0.6 m^3, leaving enough space for any racks to be installed in between. Finally, the energy and CO_2 emissions for the storage of the material for the 100 ribs (considering a period of 18 months or 1.5 years) are calculated as follows:

$$\begin{aligned} E_{storage} &= 14.64 \cdot 3.37 \cdot 1.5 \\ &= 74.1MJ \end{aligned} \tag{3.46}$$

$$\begin{aligned} CO_{2_{storage}} &= 1.654 \cdot 3.37 \cdot 1.5 \\ &= 8.4kg \end{aligned} \tag{3.47}$$

For cutting of the material, the same equations as for sheet metal can be used, with one modification being that the multiplication by 2 for each rib is not necessary anymore. This is due to the fact that for the metal sheets, two halves had to be cut and then assembled together. While for composites a larger number of plies will have to be cut, the cutting/trimming time per rib is kept at 0.5 h, with the reason being that the plies do not need to have the perfect geometry this time, and they can be trimmed all together after layup, which takes considerably less time than cutting them individually. Considering that on average, prepreg plies have a thickness of 0.18 mm [51], and that the thickness of the ribs is of 6.95 mm, roughly 38.6 plies will be required (round up to 40 for symmetry) which would result in very high processing times if individual cutting would be considered. The final energy and CO_2 emissions calculations can be seen below:

$$\begin{aligned} E_{cutting} &= 172.8 \cdot 0.5 \cdot 100 \\ &= 8640MJ \end{aligned} \tag{3.48}$$

$$\begin{aligned} CO_{2_{cutting}} &= 19.526 \cdot 0.5 \cdot 100 \\ &= 976.3kg \end{aligned} \tag{3.49}$$

The next energy consuming step is the autoclave curing. For this, the energy is calculated by taking the specific 23 MJ/kg consumption found for the process and multiplying it by the weight of the rib which has to cure and finally by the total number of ribs.

$$\begin{aligned} E_{autoclave} &= 23 \cdot 2.1 \cdot 100 \\ &= 4830MJ \end{aligned} \tag{3.50}$$

$$\begin{aligned} CO_{2_{autoclave}} &= 2.6 \cdot 2.1 \cdot 100 \\ &= 546kg \end{aligned} \tag{3.51}$$

For NDI of the composites, ultrasound scans are performed (one A-scan and one C-scan). Each of these were found to consume the same amount of energy and therefore have a similar amount of CO_2 emitted as well. The energy can be calculated in this case by multiplying the 80 MJ/m^2 by the total area of the ribs and of course the total number of ribs. Since the two processes are essentially identical, the reported numbers below will be a sum of the two.

$$\begin{aligned} E_{NDI} &= 80 \cdot 0.36 \cdot 100 \cdot 2 \\ &= 5757.3MJ \end{aligned} \tag{3.52}$$

$$\begin{aligned} CO_{2_{NDI}} &= 9.04 \cdot 0.36 \cdot 100 \cdot 2 \\ &= 650.6kg \end{aligned} \tag{3.53}$$

For painting and curing, since the geometries of the parts remain the same as for metals, the numbers do not change. The same can be said about the operational phase as a whole.

Lastly, for the recycling, the prepregs can only be combusted in order to gain some energy. This is different from the metals where energy had to be put into the process. As a result of this, the numbers which are used in this situation are negative. To calculate the total energy gained, the specific energy obtained out of combustion is multiplied by the amount of material combusted. This includes the wing rib and the additional material which was cut away during production. In the case of the CO_2, the numbers remain positive since the emissions are present regardless of whether energy is gained out of or put into the process.

$$
\begin{aligned}
E_{combustion} &= -32.9 \cdot 3.5 \cdot 100 \\
&= -11515MJ
\end{aligned}
\tag{3.54}
$$

$$
\begin{aligned}
CO2_{combustion} &= 3.33 \cdot 3.5 \cdot 100 \\
&= 1165.5kg
\end{aligned}
\tag{3.55}
$$

The summary of all results for the production of 100 ribs for this material can be seen in Figure 3.8 and the bar charts in Figure 3.9 and Figure 3.10.

Energy and CO2	Specific Epoxy CFRP Prepreg				Total Epoxy CFRP Prepreg				%
	Energy	Unit	CO2	Unit	Energy	Unit	CO2	Unit	
Raw material production	723	MJ/kg	101.943	kg/kg	253050.0	MJ	35680.1	kg	100.00
Transport									
____Cooling	0	N/A	0	N/A	0.0	N/A	0.0	N/A	0.00
____Air (LH)	6.5	MJ/(t*km)	0.072	kg/MJ	12967.5	MJ	933.7	kg	100.00
Cooled storage	14.64	MJ/(year*m3)	1.654	kg/(year*m3)	74.1	MJ	8.4	kg	100.00
Thawing	0	N/A	0	N/A	0.0	N/A	0.0	N/A	100.00
Cutting (incl. final trimming)									
___Plasma	172.8	MJ/h	19.526	kg/hour	8640.0	MJ	976.3	kg	0.00
___Mechanical	0	N/A	0	N/A	0.0	N/A	0.0	N/A	100.00
Layup									
____Hand	0	N/A	0	N/A	0.0	N/A	0.0	N/A	100.00
____ATL/AFP	0	N/A	0	N/A	0.0	N/A	0.0	N/A	100.00
Autoclave	23	MJ/kg	2.6	kg/kg	4830.0	MJ	546.0	kg	100.00
NDI									
____A-scan	80	MJ/m2	9.04	kg/m2	2878.6	MJ	325.3	kg	100.00
____C-scan	80	MJ/m2	9.04	kg/m2	2878.6	MJ	325.3	kg	100.00
Painting	0	N/A	0	N/A	0.0	N/A	0.0	N/A	100.00
Curing/drying	117	MJ/batch	13.221	kg/batch	117.0	MJ	13.2	kg	100.00
Operational phase	0.00172	MJ/(kg*km)	0.000124	kg/(kg*km)	30517990.3	MJ	2200134.2	kg	100.00
Recycling (combustion)	-32.9	MJ/kg	3.33	kg/kg	-11515.0	MJ	1165.5	kg	100.00

Totals for 100 ribs	**3.0783E+07**	**MJ**	2.2391E+06	**kg**
Of which:	Epoxy CFRP Prepreg		Epoxy CFRP Prepreg	
Raw material	2.5305E+05	MJ	3.5680E+04	kg
Transport	1.2968E+04	MJ	9.3366E+02	kg
Production	1.0778E+04	MJ	1.2182E+03	kg
Operational	3.0518E+07	MJ	2.2001E+06	kg
Recycling	-1.1515E+04	MJ	1.1655E+03	kg

Figure 3.8: Energy and CO_2 calculations summary for Epoxy CFRP Prepreg

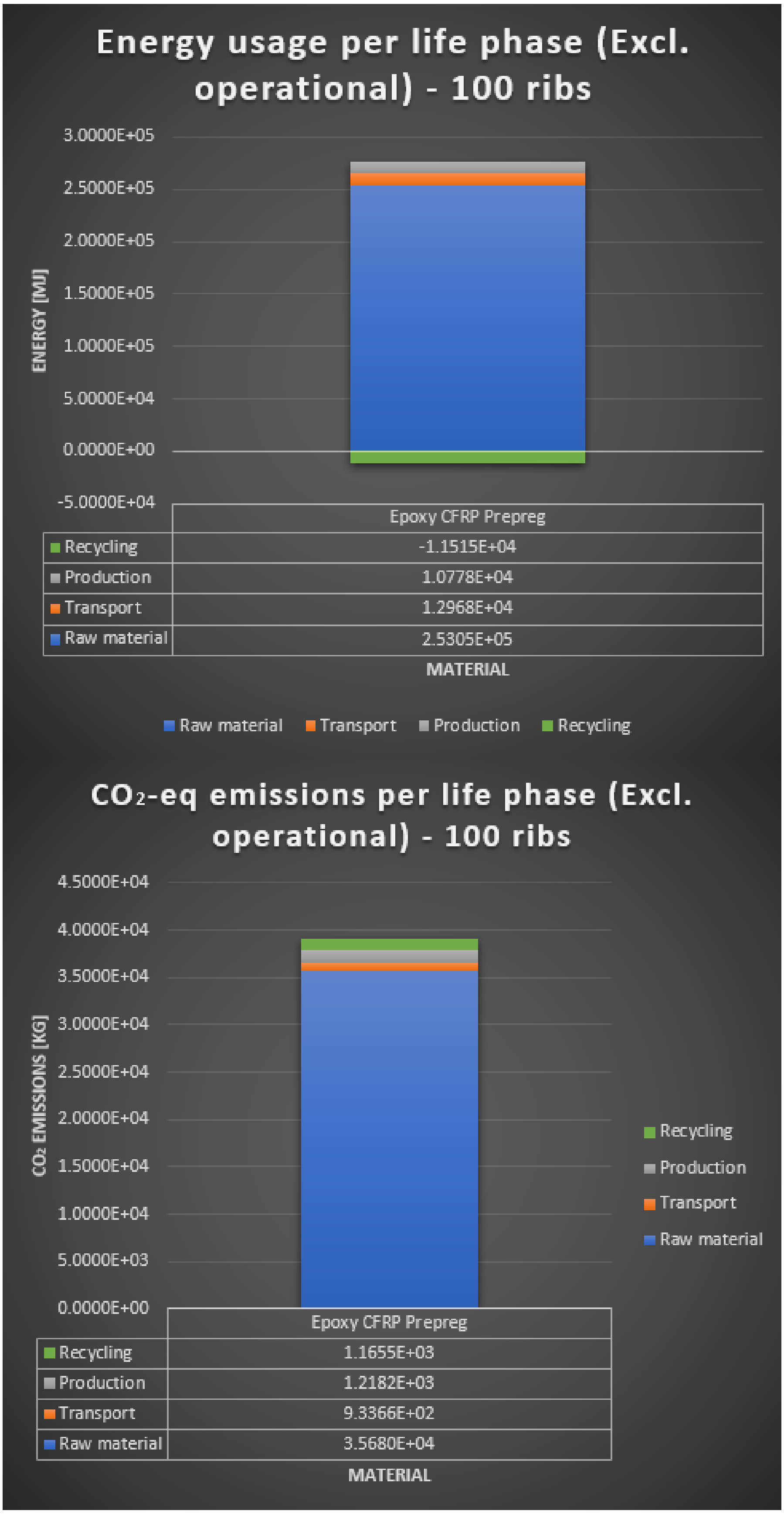

Figure 3.9: Epoxy CFRP prepreg energy and CO_2 per life stage charts (excluding the operational phase)

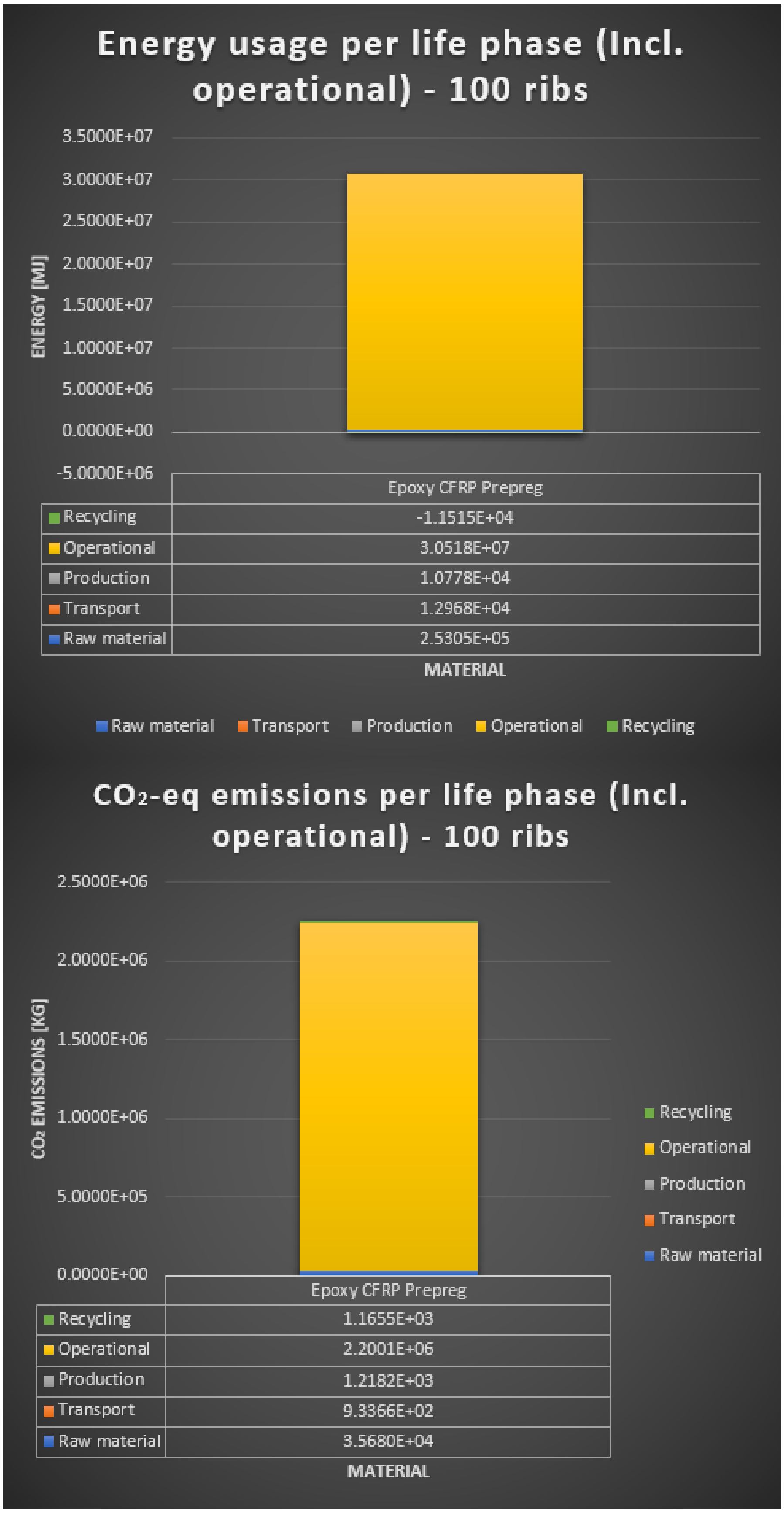

Figure 3.10: Epoxy CFRP prepreg energy and CO_2 per life stage charts (including the operational phase)

3.2.4. Thermoset Epoxy-CFRP RTM composite

For the composite made using RTM, some changes occur in the methodology compared to the prepreg version, since now the raw materials are separated into dry fibres and the resin. It is assumed that the composites have a 60% fibre percentage (by volume). The density of the fibres was found at 1840 kg/m^3 and that of the resin at 1400 kg/m^3 using EduPack [3]. Using this data, the fibre volume by weight can be found at 66.35%[1].

Assumption
The composite's fibre fraction volume is 60%.

Once again, the material going into the process is not at a 1:1 ratio to that coming out as a rib. It is assumed that all ribs have the same geometry, and additionally that the weights of the composite ribs are also the same. As a result, the approach for this thermoset composite, due to the two separate materials that have to be considered will be somewhat similar to what will be done with the thermoplastic one too. In the case of the thermoplastic, since the wing rib has been manufactured already, the numbers for the material amounts are known. In order to keep the original order established for the manufacturing options, the thermoset is discussed first using these numbers, and their source will be presented in the next section for the thermoplastic rib.

It is known that the starting weight of the materials for one rib stands at roughly 4.5 kg, and that the weight of the preformed rib is at 4.1 kg. Based on the fibre percentage by weight mentioned before, the individual amounts of fibres and resin at the two stages (raw material and preform), are given in Table 3.7. In this table, an additional row is added for the total amount of resin. On this last row, an additional of 20% is added to the raw material entering the process since as it was mentioned in chapter 2, during an RTM process it is preferred to have a larger amount of resin than needed in order to prevent incomplete infusion, and this estimated additional amount is at 20% **[Wesley McNulty, personal communication, 22.06.2022]**.

Table 3.7: Fibre and resin amounts for the RTM process

Weight distribution	Raw material	Preform
Total weight [kg]	4.5	4.1
Fibre weight [kg]	2.99	2.72
Resin weight [kg]	1.51	1.38
Total resin (incl. RTM margin) [kg]	1.82	

Starting once again with the calculations for the raw material, these are for the most part identical to what was done this far for the other materials, with the exception that now two components are considered separately. Additionally, in Table 2.6 it can be seen that there are three values that are provided for the general manufacturing of carbon fibre. The first is for the production of the fibres, the second for the production of the fabric and the last one for the production of prepreg material. In this situation, the energy will be calculated by considering a sum of the energy for primary fibre production and the fabric since RTM processes do not use prepregs. The calculations can be seen in the equations below:

$$E_{raw(fibre)} = (300 + 2.73) \cdot 2.99 \cdot 100 = 90387.6MJ \tag{3.56}$$

$$CO_{2_{raw(fibre)}} = (42.3 + 0.385) \cdot 2.99 \cdot 100 = 12744.7kg \tag{3.57}$$

$$E_{raw(epoxy)} = 135 \cdot 1.82 \cdot 100 = 24530.9MJ \tag{3.58}$$

$$CO_{2_{raw(epoxy)}} = 19.04 \cdot 1.82 \cdot 100 = 3458.8kg \tag{3.59}$$

[1] https://compositesevolution.com/resources/volume-weight-fraction-calculator/

Moving onto transport, the cooling remains under the same conditions as for the previous material. In this case however it is only the resin that has to be kept cool, since the fibres are still dry and therefore do not have a shelf life. The transportation energy is calculated the same as before, with the only change being the source and the distance to it (5700 km).

$$E_{air} = \frac{6.5 \cdot 5700 \cdot (2.99 + 1.82) \cdot 100}{1000} \tag{3.60}$$
$$= 17794.6MJ$$
$$CO_{2_{air}} = 0.072 \cdot 17794.6 \tag{3.61}$$
$$= 1281.2kg$$

For the cooled storage, as mentioned before this time only the resin needs to be considered. Taking into account the mass of resin that is used for one rib (1.82 kg), and the density of resin of 1400 kg/m^3, it can be calculated that for 100 ribs, the total volume of resin will be of roughly 0.13 m^3.

$$E_{storage} = 14.64 \cdot 0.13 \cdot 1.5 \tag{3.62}$$
$$= 2.9MJ$$
$$CO_{2_{storage}} = 1.654 \cdot 0.13 \cdot 1.5 \tag{3.63}$$
$$= 0.3kg$$

For cutting, since mechanical cutting is considered again, the process energy and CO_2-eq emissions remain negligible.

The next step before the RTM infusion process is to make the preform. The energy for this is calculated by multiplying the specific energy of 10.6 MJ/kg by the mass of the fibres in the preformed rib since at this point in the process there is no resin in the preform. This results in the following:

$$E_{preform} = 10.6 \cdot 2.72 \cdot 100 \tag{3.64}$$
$$= 2883.6MJ$$
$$CO_{2_{preform}} = 1.198 \cdot 2.72 \cdot 100 \tag{3.65}$$
$$= 325.9kg$$

After the preform is made, it is then placed into the infusion mould where the resin will be added. This process has a specific energy of 380 MJ/hour as determined in chapter 2. The exact time for the infusion of this rib is however unknown since it has not been manufactured this way. The infusion times can also vary greatly depending on the pressures used in the RTM process and the number and positioning of the inlets for the resin. According to Techni-Modul Engineering, for a wing rib with dimensions of 0.7 m x 0.2 m which is very close to those of the rib under consideration for this project, using high pressure RTM, the infusion would usually last around 40 minutes [20]. Other sources report that typical process times will vary from 30 minutes to 1 hour [21]. As a result, it was decided to go for an arbitrary infusion time of 1 hour for this analysis.

Assumption
RTM infusion time for one rib is considered to be 1 hour.

$$E_{infusion} = 380 \cdot 1 \cdot 100 \tag{3.66}$$
$$= 38000MJ$$
$$CO_{2_{infusion}} = 42.94 \cdot 1 \cdot 100 \tag{3.67}$$
$$= 4294kg$$

The remaining steps including NDI, painting/drying and the operational phase all have identical numbers to what was calculated for the Epoxy CFRP prepreg wing rib. For the autoclave curing step, it is important to note that for the study at hand it has not been added to the calculations, since the numbers obtained for RTM infusion include curing energy too (as per the process description from chapter 2). As a result, this number is kept in the table but is not added to the total energy consumption for the flow. If this number is to be used in any other analysis, the corresponding energy value should be subtracted from the RTM energy numbers.

Lastly, for the recycling, both the epoxy and the carbon fibres in this rib are non recyclable, but they can be combusted in order to gain some energy. The specific energies of each need to be multiplied by the mass of material that entered production and then once again multiplied by the total number of ribs. The end result is obtained by summing the energy obtained from combusting each of the components, and the same can be done for the CO_2 emissions.

$$\begin{aligned} E_{comb(fibre)} &= -33.6 \cdot 2.99 \cdot 100 \\ &= -100032.1MJ \end{aligned} \tag{3.68}$$

$$\begin{aligned} CO2_{comb(fibre)} &= 3.76 \cdot 2.99 \cdot 100 \\ &= 1122.6kg \end{aligned} \tag{3.69}$$

$$\begin{aligned} E_{comb(epoxy)} &= -31.5 \cdot 1.82 \cdot 100 \\ &= -5723.9MJ \end{aligned} \tag{3.70}$$

$$\begin{aligned} CO2_{comb(epoxy)} &= 2.54 \cdot 1.82 \cdot 100 \\ &= 461.5kg \end{aligned} \tag{3.71}$$

This concludes the calculations for this material as well, and a summary can once again be seen in Figure 3.11 with the bar charts for the production of 100 ribs in Figure 3.12 and Figure 3.13.

Energy and CO2	Specific Epoxy CFRP RTM Energy	Unit	CO2	Unit	Total Epoxy CFRP RTM Energy	Unit	CO2	Unit	%
Raw material production									
____Epoxy	135	MJ/kg	19.035	kg/kg	24530.9	MJ	3458.8	kg	100.00
____Fibre	302.73	MJ/kg	42.685	kg/kg	90387.6	MJ	12744.7	kg	100.00
Transport									
_____Cooling	0	N/A	0	N/A	0.0	N/A	0.0	N/A	0.00
_____Air (LH)	6.5	MJ/(t*km)	0.072	kg/MJ	17794.6	MJ	1281.2	kg	100.00
Cooled storage	14.64	MJ/(year*m3)	1.654	kg/(year*m3)	2.9	MJ	0.3	kg	100.00
Cutting (incl. final trimming)									
___Plasma	172.8	MJ/h	19.526	kg/hour	8640.0	MJ	976.3	kg	0.00
___Mechanical	0	N/A	0	N/A	0.0	N/A	0.0	N/A	100.00
Layup									
____Hand	0	N/A	0	N/A	0.0	N/A	0.0	N/A	100.00
Preform	10.6	MJ/kg	1.198	kg/kg	2883.6	MJ	325.9	kg	100.00
RTM infusion	380	MJ/hour	42.94	kg/hour	38000.0	MJ	4294.0	kg	100.00
Autoclave	23	MJ/kg	2.6	kg/kg	4830.0	MJ	546.0	kg	100.00
NDI									
____A-scan	80	MJ/m2	9.04	kg/m2	2878.6	MJ	325.3	kg	100.00
____C-scan	80	MJ/m2	9.04	kg/m2	2878.6	MJ	325.3	kg	100.00
Painting	0	N/A	0	N/A	0.0	N/A	0.0	N/A	100.00
Curing/drying	117	MJ/batch	13.221	kg/batch	117.0	MJ	13.2	kg	100.00
Operational phase	0.00172	MJ/(kg*km)	0.000124	kg/(kg*km)	30517990.3	MJ	2200134.2	kg	100.00
Recycling (combustion)									
___Epoxy (combust)	-31.5	MJ/kg	2.54	MJ/kg	-5723.9	MJ	461.5	kg	100.00
___CF (combust)	-33.6	MJ/kg	3.76	MJ/kg	-10032.1	MJ	1122.6	kg	100.00

Totals for 100 ribs	3.0682E+07	MJ	2.2245E+06	kg
Of which:	Epoxy CFRP RTM		Epoxy CFRP RTM	
Raw material	1.1492E+05	MJ	1.6204E+04	kg
Transport	1.7795E+04	MJ	1.2812E+03	kg
Production	4.6761E+04	MJ	5.2840E+03	kg
Operational	3.0518E+07	MJ	2.2001E+06	kg
Recycling	-1.5756E+04	MJ	1.5842E+03	kg

Figure 3.11: Energy and CO_2 calculations summary for Epoxy CFRP RTM

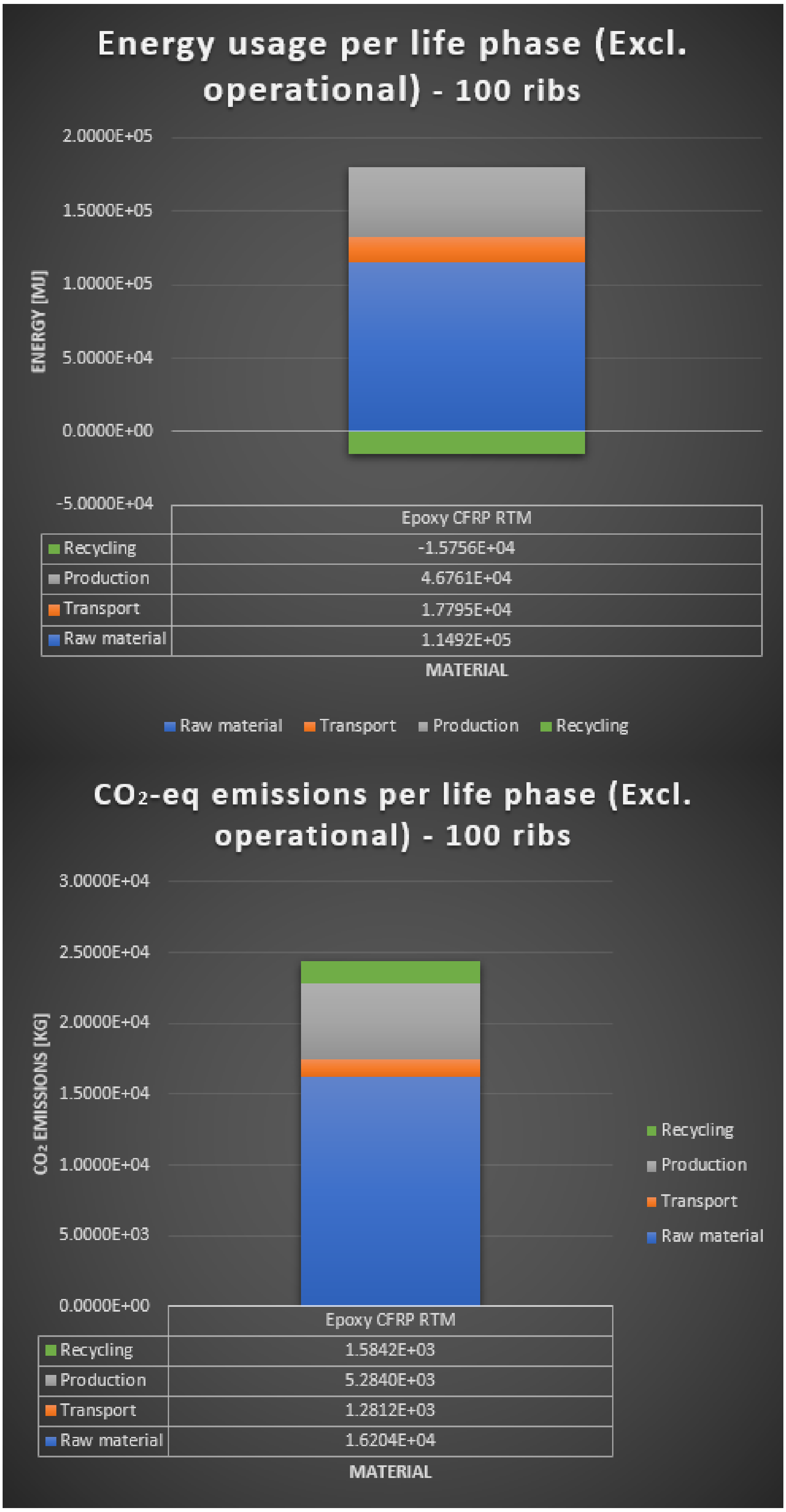

Figure 3.12: Epoxy CFRP RTM energy and CO_2 per life stage charts (excluding the operational phase)

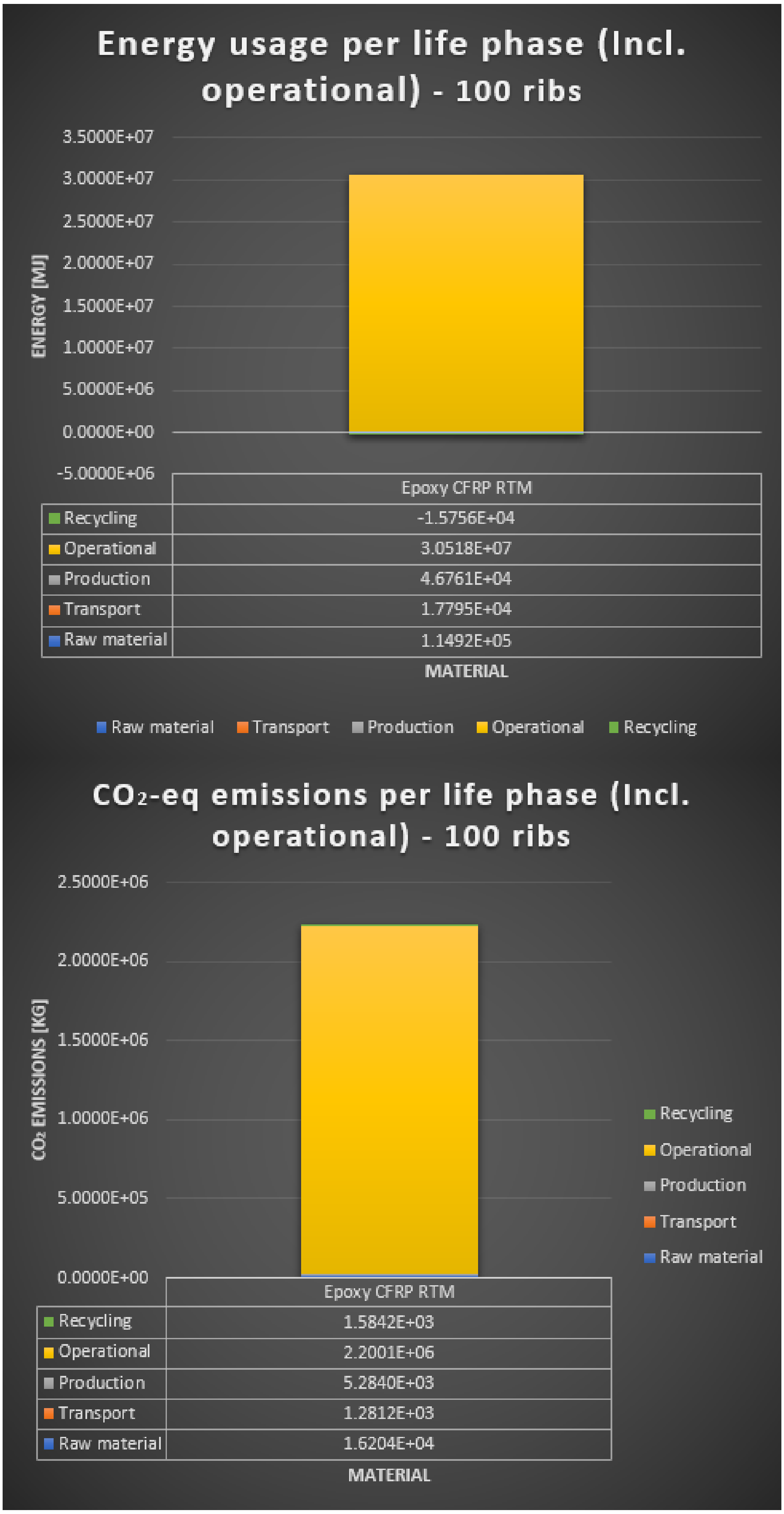

Figure 3.13: Epoxy CFRP RTM energy and CO_2 per life stage charts (including the operational phase)

3.2.5. Thermoplastic PEKK-CFRP out-of-autoclave consolidated composite

As mentioned before, the numbers used for the rib weights at different stages of production in the case of the thermoset RTM rib were taken directly from the weights of the thermoplastic rib. It was provided by GKN, that a total of 4.5 kg of laminates is required for producing one thermoplastic rib **[Marc Koetsier, personal communication, 25.08.2022]** and that the preform of the rib (before final cutting and trimming) is of 4.1kg. Knowing that the fibre volume fraction is still at 60%, the density of carbon fibre is 1840 kg/m^3 and that of the PEKK resin is 1320 kg/m^3, the fibre volume by weight is this time determined at 67.65%. Table 3.8 the distribution of weight in the thermoplastic rib at the raw material stage and the preform version of the rib.

Table 3.8: Fibre and resin amounts for the OOAC (hot press consolidation) process

Weight distribution	Raw material	Preform
Total weight [kg]	4.5	4.1
Fibre weight [kg]	3.04	2.77
Resin weight [kg]	1.46	1.33

In the raw material phase, the energy and CO_2 emitted can be calculated for each of the components the same way it has been done for the other materials too, by multiplying the specific energy by the amount of material that has to enter the process. This time, as opposed to the example seen for Epoxy CFRP RTM ribs, the fibre energy is a sum of the primary production energy, and the prepreg production, since the thermoplastic material is not made into a fabric.

$$E_{raw(fibre)} = (300 + 42) \cdot 3.04 \cdot 100 \tag{3.72}$$
$$= 104113.4MJ$$
$$CO2_{raw(fibre)} = (42.3 + 5.922) \cdot 3.04 \cdot 100 \tag{3.73}$$
$$= 14680kg$$

$$E_{raw(PEKK)} = 333 \cdot 1.46 \cdot 100 \tag{3.74}$$
$$= 48476.5MJ$$
$$CO2_{raw(PEKK)} = 46.953 \cdot 1.46 \cdot 100 \tag{3.75}$$
$$= 6835.2kg$$

Same as before, for the transportation, the long haul air transportation was selected and the energy was calculated by multiplying the specific energy by the distance and the weight of the materials that have to be brought in production. This weight is that of the laminates (4.5 kg per rib).

$$E_{air} = \frac{6.5 \cdot 8070 \cdot 4.5 \cdot 100}{1000} \tag{3.76}$$
$$= 23604.75MJ$$
$$CO2_{air} = 0.072 \cdot 23604.8 \tag{3.77}$$
$$= 1699.5kg$$

For thermoplastic materials, cooled storage is not required as they do not cure, and therefore that energy is skipped for this material. For cutting, once again the same cutting time and method (mechanical) are chosen and therefore the energy is negligible. Next, for the preforming step, as opposed to the previous case where the fibres were dry when entering the process, for thermoplastics the preform is made using impregnated fibres. As a result, the same equations can be used but the mass has to be changed to that of the complete preformed rib.

$$E_{preform} = 10.6 \cdot 4.1 \cdot 100 \tag{3.78}$$
$$= 4346MJ$$
$$CO2_{preform} = 1.198 \cdot 4.1 \cdot 100 \tag{3.79}$$
$$= 491.2kg$$

For the out of autoclave consolidation, primary data from the rib manufacturing was used, and 82 MJ of energy were calculated to be required for one rib and 2.6 kg of CO_2 to be produced. As a result, the total energy is calculated simply by multiplying this number by the number of ribs.

$$E_{OOAC} = 82 \cdot 100 \tag{3.80}$$
$$= 8200MJ$$
$$CO_{2_{OOAC}} = 2.6 \cdot 100 \tag{3.81}$$
$$= 260kg$$

Once again, for the NDI and painting/drying steps the energy and CO_2 production remain the same, and so does the operational phase. Lastly, for the recycling, the approach changes compared to all other composite ribs considered so far. This is due to the fact that PEKK is a thermoplastic resin and therefore it can be recycled as well, as opposed to epoxy which could only be combusted. A description of the recycling process has been given in chapter 2 under the end of life of the thermoplastic PEKK-CFRP out-of-autoclave consolidated composite.

Despite the current work into thermoplastic recycling, according to data from CES EduPack, only 0.1% of the PEKK resin currently in production is recycled [3], and in the absence of further data on the recycling of a full thermoplastic CFRP part, this number was used for the recycling energy estimations. It is therefore assumed that 0.1% of the resin is recycled, while the rest is combusted together with the fibres. The energy and CO_2 produced can therefore be calculated as follows:

$$E_{recycle(PEKK)} = 113 \cdot 1.46 \cdot 100 \cdot 0.001 \tag{3.82}$$
$$= 16.4MJ$$
$$CO_{2_{recycle(PEKK)}} = 12.796 \cdot 1.46 \cdot 100 \cdot 0.001 \tag{3.83}$$
$$= 1.9kg$$
$$E_{comb(PEKK)} = -31 \cdot 1.46 \cdot 100 \cdot 0.999 \tag{3.84}$$
$$= -4508.3$$
$$CO_{2_{comb(PEKK)}} = 3.01 \cdot 1.46 \cdot 100 \cdot 0.999 \tag{3.85}$$
$$= 437.7kg$$
$$E_{comb(fibre)} = -33.6 \cdot 3.04 \cdot 100 \tag{3.86}$$
$$= -10228.7MJ$$
$$CO_{2_{comb(fibre)}} = 3.76 \cdot 3.04 \cdot 100 \tag{3.87}$$
$$= 1144.6kg$$

This concludes the calculations for the last material considered in this study, and the summary can be seen in Figure 3.14 with the bar charts for the production of 100 ribs in Figure 3.15 and Figure 3.16.

Energy and CO2	Specific PEKK CFRP OOAC				Total PEKK CFRP OOAC				%
	Energy	Unit	CO2	Unit	Energy	Unit	CO2	Unit	
Raw material production									
____PEKK	333	MJ/kg	46.953	kg/kg	48476.5	MJ	6835.2	kg	100.00
____Fibre	342	MJ/kg	48.222	kg/kg	104113.4	MJ	14680.0	kg	100.00
Transport									
_____Air (LH)	6.5	MJ/(t*km)	0.072	kg/MJ	23604.8	MJ	1699.5	kg	100.00
Storage	0	N/A	0	N/A	0.0	N/A	0.0	N/A	100.00
Cutting (incl. final trimming)									
___Plasma	172.8	MJ/h	19.526	kg/hour	8640.0	MJ	976.3	kg	0.00
___Mechanical	0	N/A	0	N/A	0.0	N/A	0.0	N/A	100.00
Layup									
____Hand	0	N/A	0	N/A	0.0	N/A	0.0	N/A	100.00
____ATL/AFP	0	N/A	0	N/A	0.0	N/A	0.0	N/A	100.00
Preform	10.6	MJ/kg	1.198	kg/kg	4346.0	MJ	491.2	kg	100.00
OOA Consolidation	82	MJ/rib	2.6	kg/kg	8200.0	MJ	260.0	kg	100.00
NDI									
____A-scan	80	MJ/m2	9.04	kg/m2	2878.6	MJ	325.3	kg	100.00
____C-scan	80	MJ/m2	9.04	kg/m2	2878.6	MJ	325.3	kg	100.00
Painting	0	N/A	0	N/A	0.0	N/A	0.0	N/A	100.00
Curing/drying	117	MJ/batch	13.221	kg/batch	117.0	MJ	13.2	kg	100.00
Operational phase	0.00172	MJ/(kg*km)	0.000124	kg/(kg*km)	30517990.3	MJ	2200134.2	kg	100.00
Recycling									
___PEKK (recycle)	113	MJ/kg	12.769	MJ/kg	16.4	MJ	1.9	kg	0.10
___PEKK (combust)	-31	MJ/kg	3.01	MJ/kg	-4508.3	MJ	437.7	kg	99.90
___CF (combust)	-33.6	MJ/kg	3.76	MJ/kg	-10228.7	MJ	1144.6	kg	100.00

Totals for 100 ribs	**3.0698E+07**	**MJ**	2.2263E+06	**kg**
Of which:	PEKK CFRP OOAC		PEKK CFRP OOAC	
Raw material	1.5259E+05	MJ	2.1515E+04	kg
Transport	2.3605E+04	MJ	1.6995E+03	kg
Production	1.8420E+04	MJ	1.4150E+03	kg
Operational	3.0518E+07	MJ	2.2001E+06	kg
Recycling	-1.4721E+04	MJ	1.5842E+03	kg

Figure 3.14: Energy and CO_2 calculations summary for PEKK CFRP OOAC (hot press consolidation)

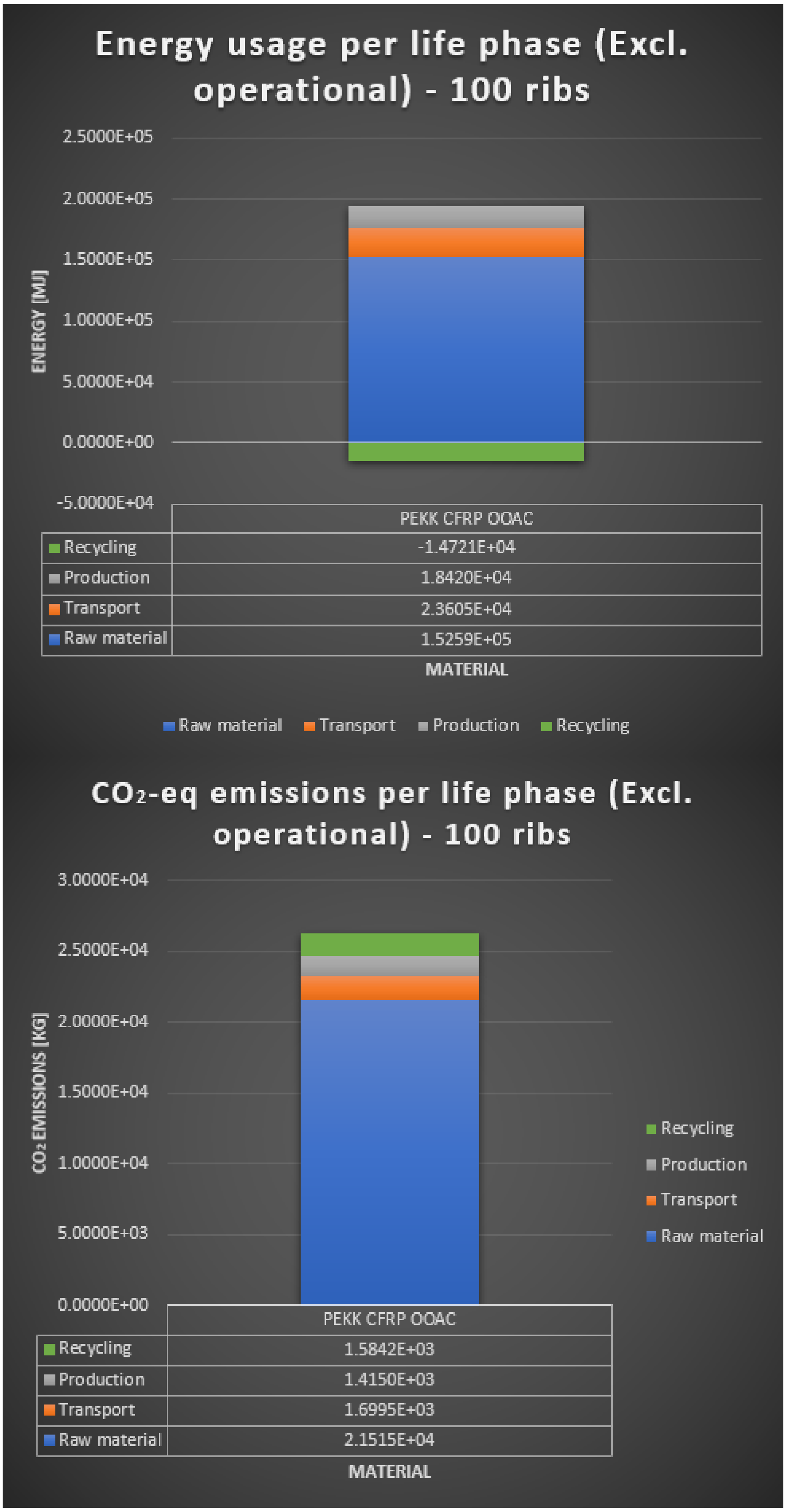

Figure 3.15: PEKK CFRP OOAC (hot press consolidation) energy and CO_2 per life stage charts (excluding the operational phase)

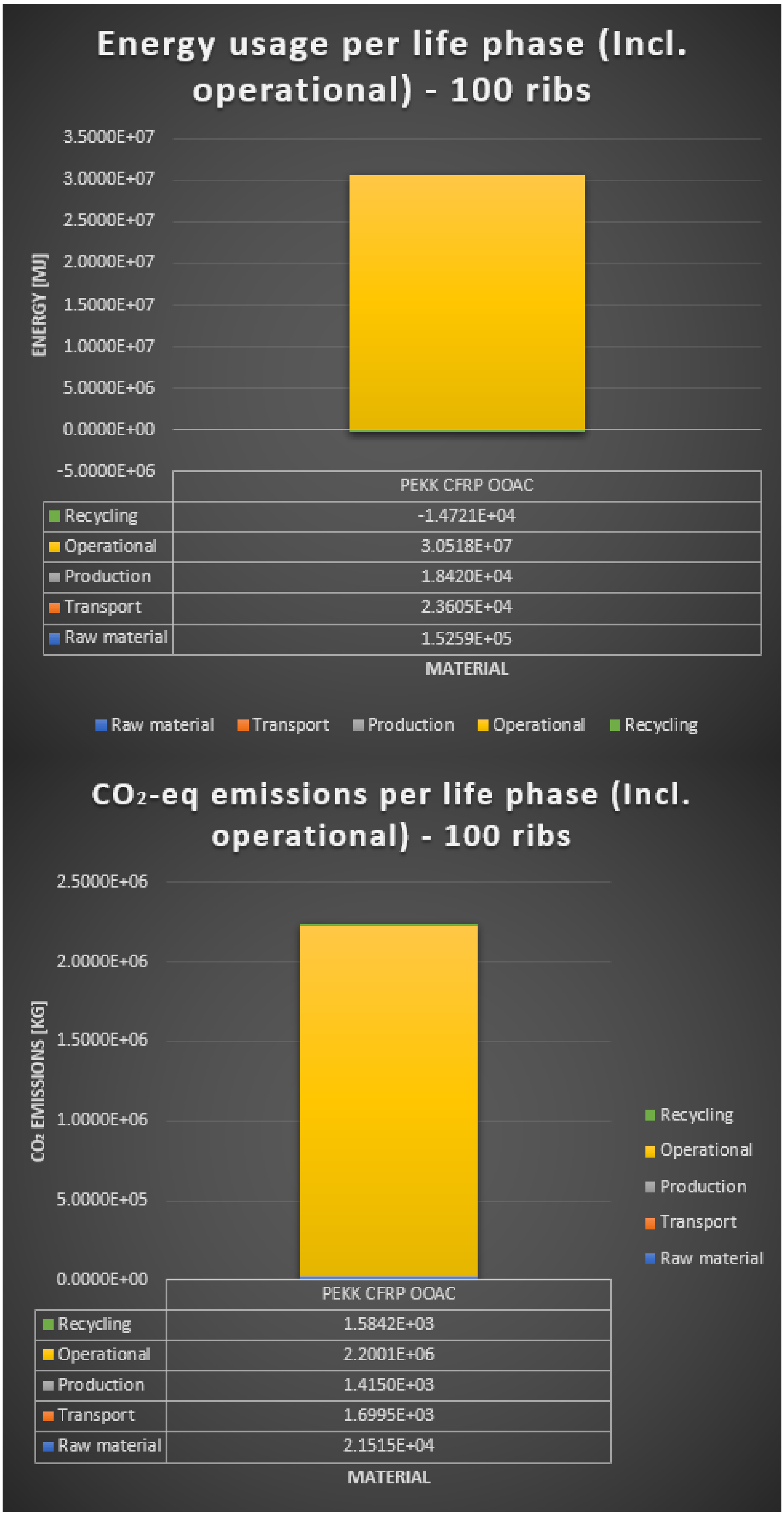

Figure 3.16: PEKK CFRP OOAC (hot press consolidation) energy and CO_2 per life stage charts (including the operational phase)

3.3. Impact assessment

For the impact assessment in this study, only a brief discussion of the impact of the processes considered thus far will be made. In order to do so, an impact category has to be selected. This choice was indirectly made when the energy consumption and CO_2 emissions were chosen for the sustainability analysis. Within the ecosystem deterioration macro-category, these two items would fall under the global warming impact category [49]. The global warming potential has been described in chapter 1 to be measured based on the amount of greenhouse gasses emitted during the processes. According to both the course on sustainability attended during the thesis duration [49] and ISO 14040 [27], the global warming potential can be calculated by use of category indicators. This requires the inputs (kg), the GWP density (kg CO_2-eq/kg), with their multiplication resulting in the total GWP (kg CO_2). These were already shown in the bar charts for all the materials presented in the previous subsection. For convenience these results will be repeated here, with the mention that the ones of interest are the amounts of CO_2 including the operational phase of the rib, since the LCA was conducted for the entire life cycle of the part.

In the case of machined aluminium, the total amount of CO_2-eq for 100 ribs was calculated at roughly $3.94 \cdot 10^6$ kg for both the Al7075 and Al7050 alloys, and the distribution per life phase can be seen in Figure 3.4. For the sheet formed aluminium, both alloys ended up with a total of $3.85 \cdot 10^6$ kg and the distribution can be seen in Figure 3.7. For composites, all of the options created similar levels of CO_2-eq for 100 ribs, around $2.2 \cdot 10^6$ kg, with variations only at the second decimal place. The distributions for these processes can be seen in Figure 3.10, Figure 3.13 and Figure 3.16. The highest emissions, and thus highest GWP out of the composites was for Epoxy CFRP prepreg, followed by PEKK CFRP OOAC and lastly Epoxy CFRP RTM.

3.4. Interpretation and evaluation

The last step in the LCA is the interpretation and evaluation of the results. For the purpose of this thesis, this step will be done in chapter 4 Results and Discussion, in order to avoid repeating the information.

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4 Results and Discussion (Including Sensitivity Analysis)

In this section all the materials are put side by side in order to compare the amounts of energy required and CO_2-eq emitted during the manufacture, operation and recycling of 100 wing ribs. The results are discussed and a short sensitivity analysis is performed for some of the assumptions used. Lastly a discussion is conducted regarding the impacts of fuel types on the operational phase.

Firstly, similar to what was done for individual materials in chapter 3, the graphs for both energy consumption and CO_2 emissions are presented once excluding the operational phase, and another time including it. The reason behind this choice is that as can be seen for example from Figure 4.1 and Figure 4.2, the operational phase is a dominating one, due to the 30 years lifetime set for the ribs. As a result, the remaining stages become almost unnoticeable. In addition to these graphs, charts of the relative amount of CO_2-eq per life phase (compared to the total) for the different materials considered are also shown in Figure 4.5, Figure 4.6, Figure 4.7, Figure 4.8, Figure 4.9. For these, in the case of aluminium, only Al7075 is shown, since the numbers are almost identical to the ones of Al7050.

Looking first at Figure 4.1, it can be seen that the largest energy consumption would be that of ribs manufactured using aluminium machining, which is also the current industry standard, firstly due to the convenience of obtaining an integral part starting from one block of aluminium, and not requiring additional steps such as assembly. Secondly, ribs manufactured this way will also have the appropriate thicknesses required for the application in which they are used, as opposed to sheet formed and assembled ribs for example, where the thicknesses required may be difficult to achieve. The prime reason for the high amount of energy required in the case of machined aluminium is the large percentage that needs to be machined away in the process. Having on average 95% of the material removed for one rib, generates the need for both a large amount of energy to manufacture the alloys that go in production, but also results in a large amount of energy which needs to be put into recycling, which is also clearly visible in Figure 4.1. Additionally, since the material is not (and cannot) be produced locally, transportation of the blocks of aluminium which are to be machined will also take much more energy than for other processes. A difference of a factor of roughly 22 can be seen compared to sheet formed aluminium, and between 6 to 12 times difference compared to the composites.

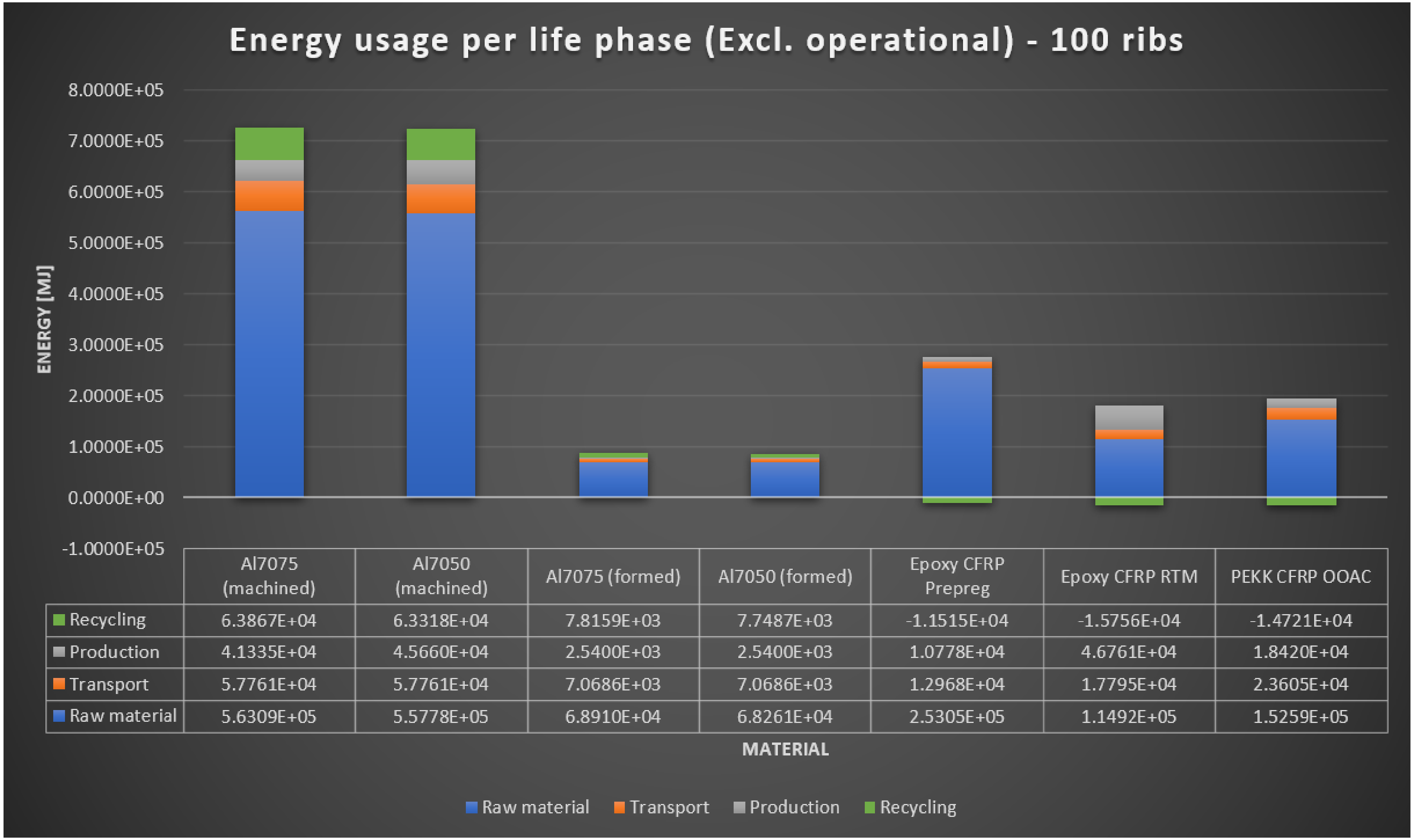
In the case of sheet formed aluminium, one may notice that for both alloys, the energy consumption was the lowest out of all other processes. As mentioned before, this comes at a cost, this being a reason why the process is typically not considered in the industry for the manufacturing of ribs. The required additional assembling processes for profiles such as the T-profile chosen for this thesis (including of course additional materials) together with the general complexity of the part and the thickness aspect mentioned before, overpower the low energy consumption. In this case however, one may notice the difference that buy-to-fly ratios will make, especially in comparison the the machined aluminium. Considering that for sheet forming only 60% of the material was assumed to be cut away (number which can also be further improved with the aid of computer software which can better nest the cuts to minimise the waste material), one can see the difference this made in the raw material production and recycling, with a rough factor of 8 difference being noticeable.

Moving onto the composite side, the thermoset rib manufactured using CFRP prepregs is the most energy consuming, with the biggest impact coming from the raw material manufacturing. Some compensation is brought here however by the production stage, where due to the manual layup selected the energy consumption is relatively low, compared to the other composites. Lastly, it is worth noticing here, that due to the combustion of the prepreg at the end of life, some of the energy is regained, which is almost enough to compensate for the transport energy required for the composite material in the first place (CO_2 is however still emitted in the process). The RTM manufactured part is the one that consumes the least amount of energy out of the composites in this study followed closely by the thermoplastic rib. With this being said however, it can be noticed that the production stage energy is higher than the production of any of the other process considered, and this is mainly due to the large amounts of heat energy required to keep the resin liquid during the infusion processes, as well as afterwards for curing purposes. Once again, for this material, the same observation can be made related to the recycling energy, which is almost enough to completely cover the transport energy. The last material considered was the thermoplastic PEKK CFRP manufactured with out of autoclave consolidation processes. This material is on the second place for energy consumption out of the three composites considered, with the largest amount of energy going once again in the raw material production stage. One limitation of the results for the composites that has to be mentioned is regarding the raw material production and therefore the numbers used as well in part processing. Due to lack of data in the case of the thermoplastic material, the raw material production was treated similarly to what was seen for the RTM thermoset. In reality, the thermoplastic material will arrive at the factory with the fibres already impregnated (prepreg form). Not having the exact numbers for the prepreg may cause errors in the calculations of the processing steps (due to approximations of the amount of resin and amount of fibres in the material), and also in the recycling phase where the energy is once again divided between resin and fibres separately rather than looking at the material as a whole.

An important discussion can be made with respect to the thermoplastic material, when it comes to its recyclability. For the purpose of this study, the recyclability of the PEKK composite was kept strictly to 0.1% compared to the 99.99% combustion fraction. This was the result of the absence of data related to recycling processes, which forced the use of the recyclability percentage found in EduPack databases. In the industry, proof of the ability of a thermoplastic composite such as PEKK CFRP to be recycled was given with the manufacturing of parts such as that seen in Figure 2.6 by GKN Aerospace. These parts however are not structural parts, since their mechanical properties are significantly below those of the original structures the material originated from. In other words, it is possible to fully recycle a PEKK CFRP composite (0% combustion), but only into a part with lower structural significance in the design. The main difference still present between the recycling of metals such as aluminium and that of thermoplastics would be in that the aluminium can be recycled from a primary structure back into a primary structure (of course, with the addition of some virgin material to the recycled mix). Regardless, the recycling of thermoplastics shows great potential for the future. In such a situation, there are a number of changes which would occur to the data seen in Figure 4.1. The energy for recycling seen in this graph is presented as an energy gain due to the use of combustion. If the material is recycled 100%, the energy will need to be put into the process rather than having it as an output. Secondly, here a choice would have to be made as to where this energy input for recycling is considered. A first option is to consider it as part of the life cycle of the wing rib, in which case the total energy will increase. The second alternative is to become a component of the life cycle of the part created as a result of the recycling process, or in other words, becoming the energy input data for the raw material production of another structure. If this choice is made, the total energy of the wing rib's life cycle will decrease. One last mention on this topic however, is that in order to be able to perform any of these calculations, direct measurements of the energy required for a recycling process for a thermoplastic component would have to be conducted. At the moment, based strictly on the information present in the databases used for this study, carbon fibre is presented as completely non-recyclable, while the recycling energy of the PEKK is given for the resin on its own. No data on the recycling energy of the combination was found.

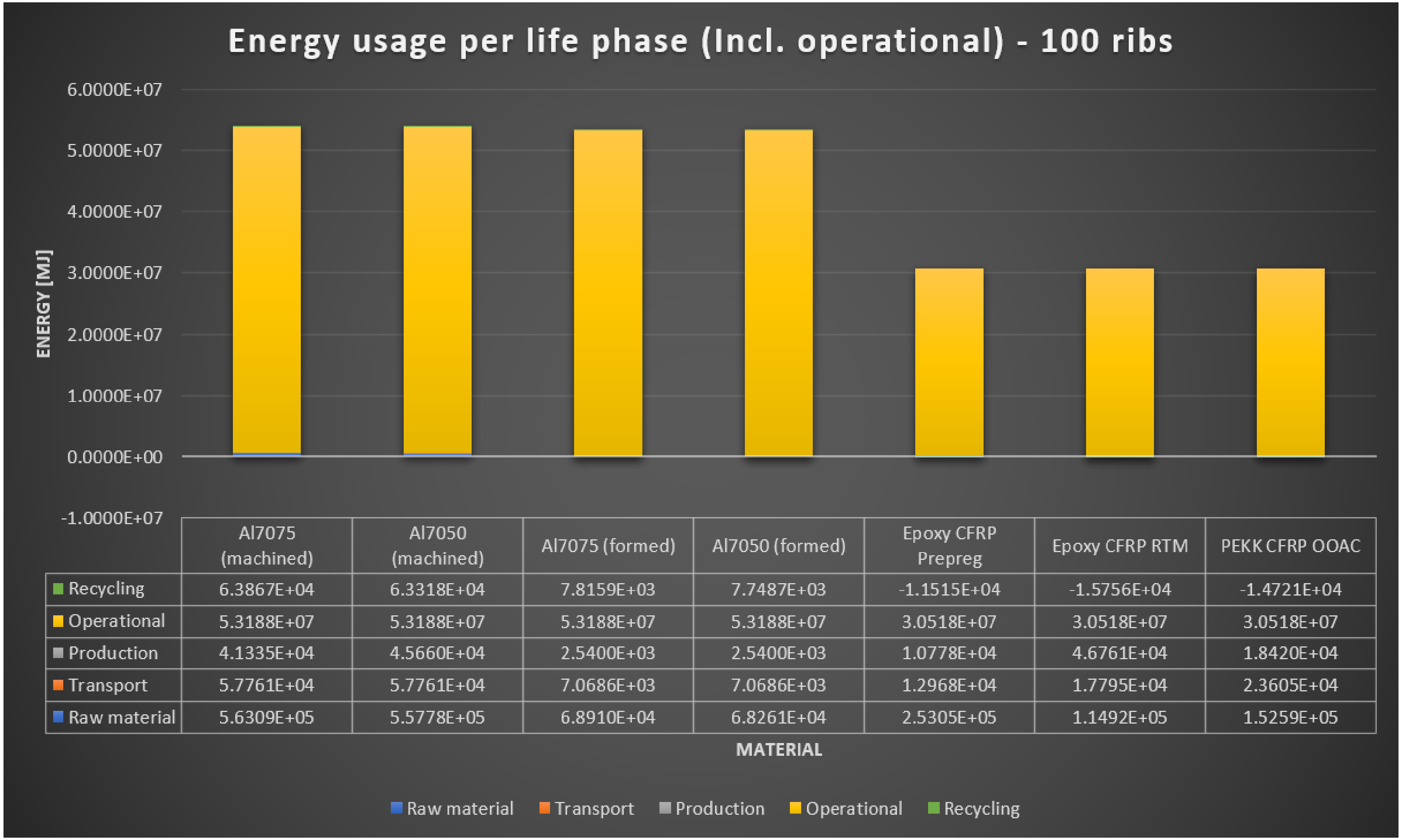
The energy consumption with the operational phase included can also be considered. It has been seen so far, that the energy for the individual processes and manufacturing routes can vary quite significantly. When looking at Figure 4.2, it can be seen however that all these variations become insignificant when the operational phase is added in the mix. Due to the long operational life of an aircraft, the critical factor affecting energy consumption becomes the weight of the components. Thus, it can be seen that all composite components which were assumed to have the same weight were calculated to require a little over half the energy of that required by their metallic counterparts.

Lastly, for the CO_2-eq emissions, these are calculated predominantly using the energy requirements per stage. As a result, the trends seen in Figure 4.3 and Figure 4.4 are identical to those in Figure 4.1 and Figure 4.2 which were discussed in the paragraphs above.



	Al7075 (machined)	Al7050 (machined)	Al7075 (formed)	Al7050 (formed)	Epoxy CFRP Prepreg	Epoxy CFRP RTM	PEKK CFRP OOAC
Recycling	6.3867E+04	6.3318E+04	7.8159E+03	7.7487E+03	-1.1515E+04	-1.5756E+04	-1.4721E+04
Production	4.1335E+04	4.5660E+04	2.5400E+03	2.5400E+03	1.0778E+04	4.6761E+04	1.8420E+04
Transport	5.7761E+04	5.7761E+04	7.0686E+03	7.0686E+03	1.2968E+04	1.7795E+04	2.3605E+04
Raw material	5.6309E+05	5.5778E+05	6.8910E+04	6.8261E+04	2.5305E+05	1.1492E+05	1.5259E+05

Figure 4.1: Energy summary for all materials (excluding the operational phase)



	Al7075 (machined)	Al7050 (machined)	Al7075 (formed)	Al7050 (formed)	Epoxy CFRP Prepreg	Epoxy CFRP RTM	PEKK CFRP OOAC
Recycling	6.3867E+04	6.3318E+04	7.8159E+03	7.7487E+03	-1.1515E+04	-1.5756E+04	-1.4721E+04
Operational	5.3188E+07	5.3188E+07	5.3188E+07	5.3188E+07	3.0518E+07	3.0518E+07	3.0518E+07
Production	4.1335E+04	4.5660E+04	2.5400E+03	2.5400E+03	1.0778E+04	4.6761E+04	1.8420E+04
Transport	5.7761E+04	5.7761E+04	7.0686E+03	7.0686E+03	1.2968E+04	1.7795E+04	2.3605E+04
Raw material	5.6309E+05	5.5778E+05	6.8910E+04	6.8261E+04	2.5305E+05	1.1492E+05	1.5259E+05

Figure 4.2: Energy summary for all materials (including the operational phase)

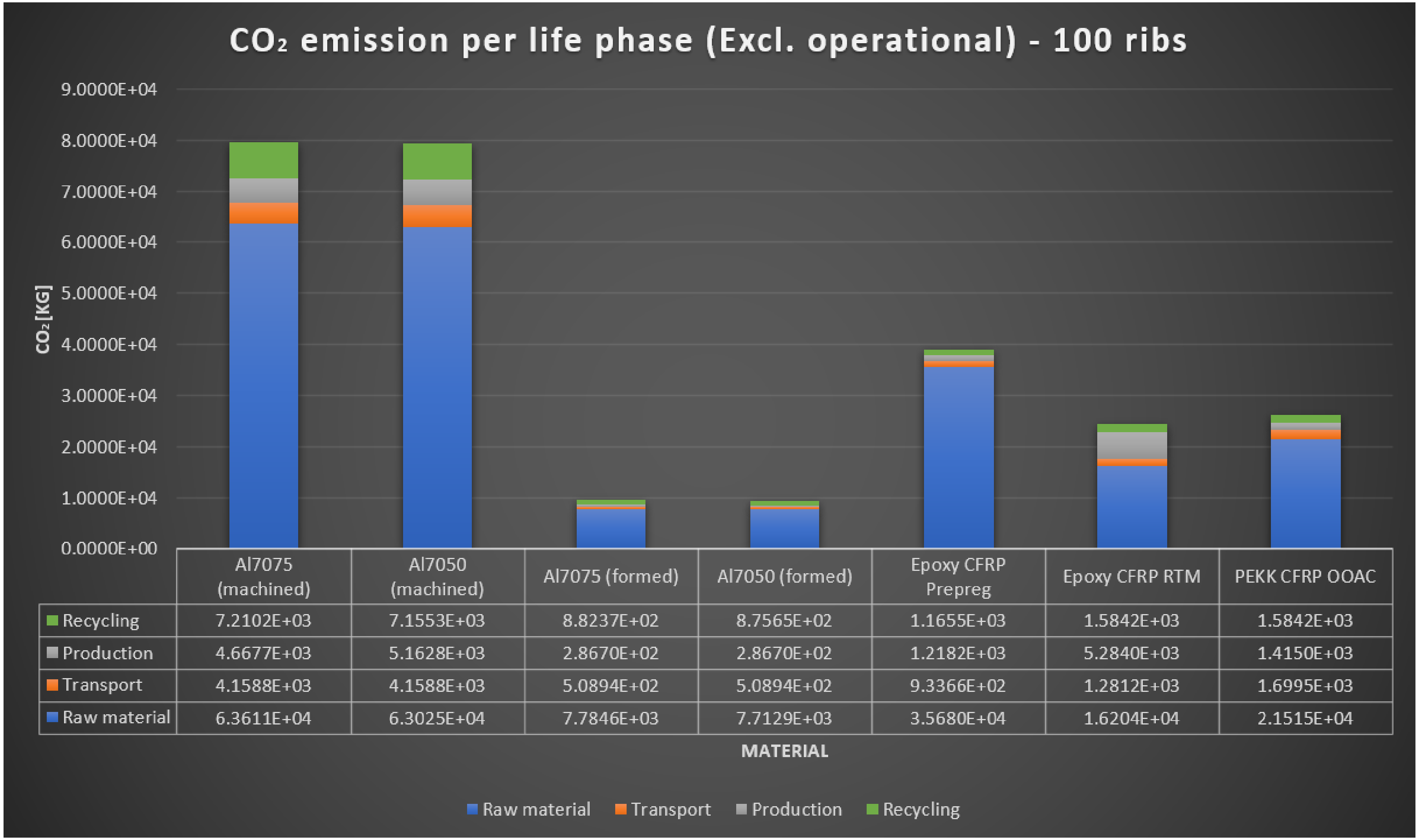


Figure 4.3: CO_2-eq summary for all materials (excluding the operational phase)

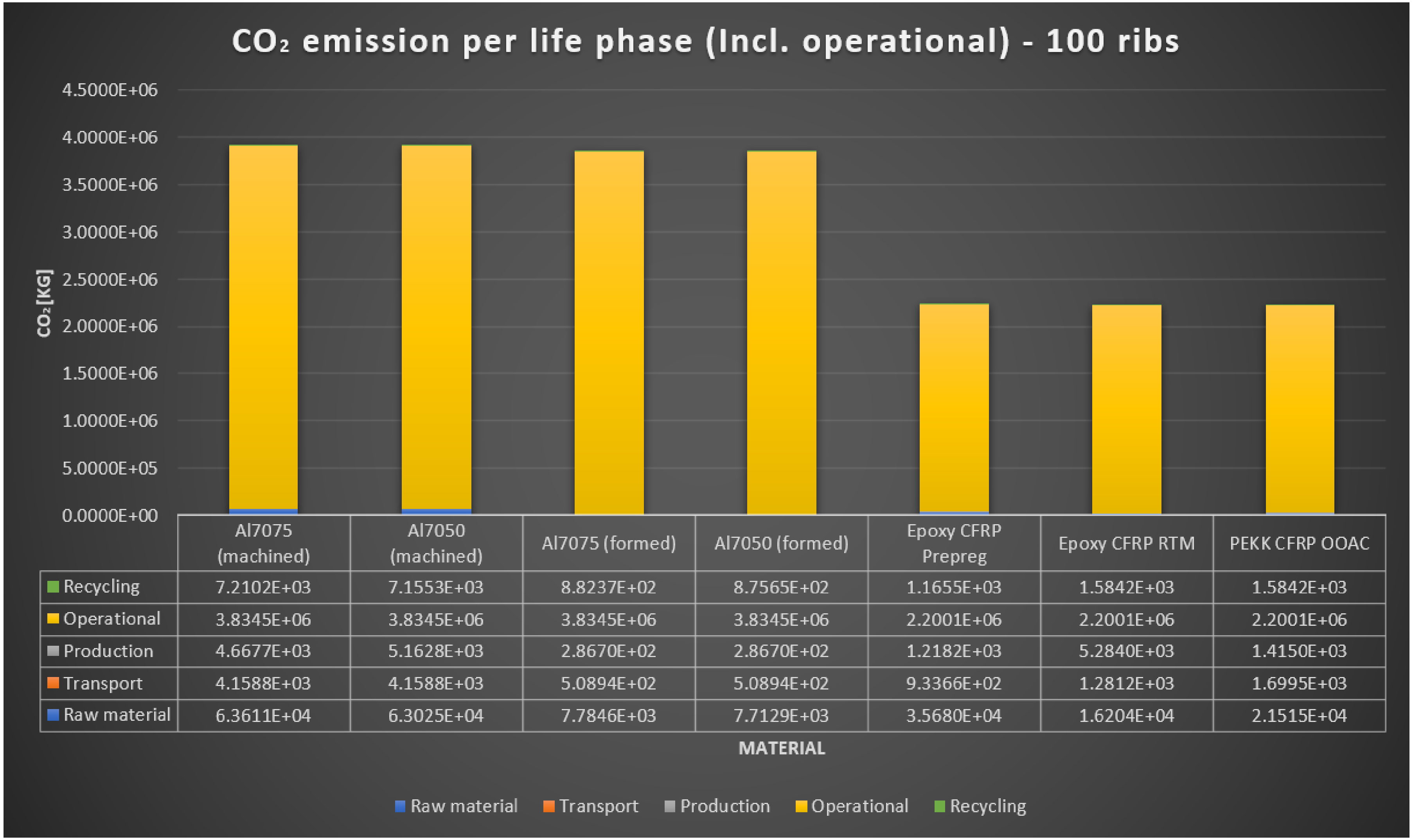


Figure 4.4: CO_2-eq summary for all materials (including the operational phase)

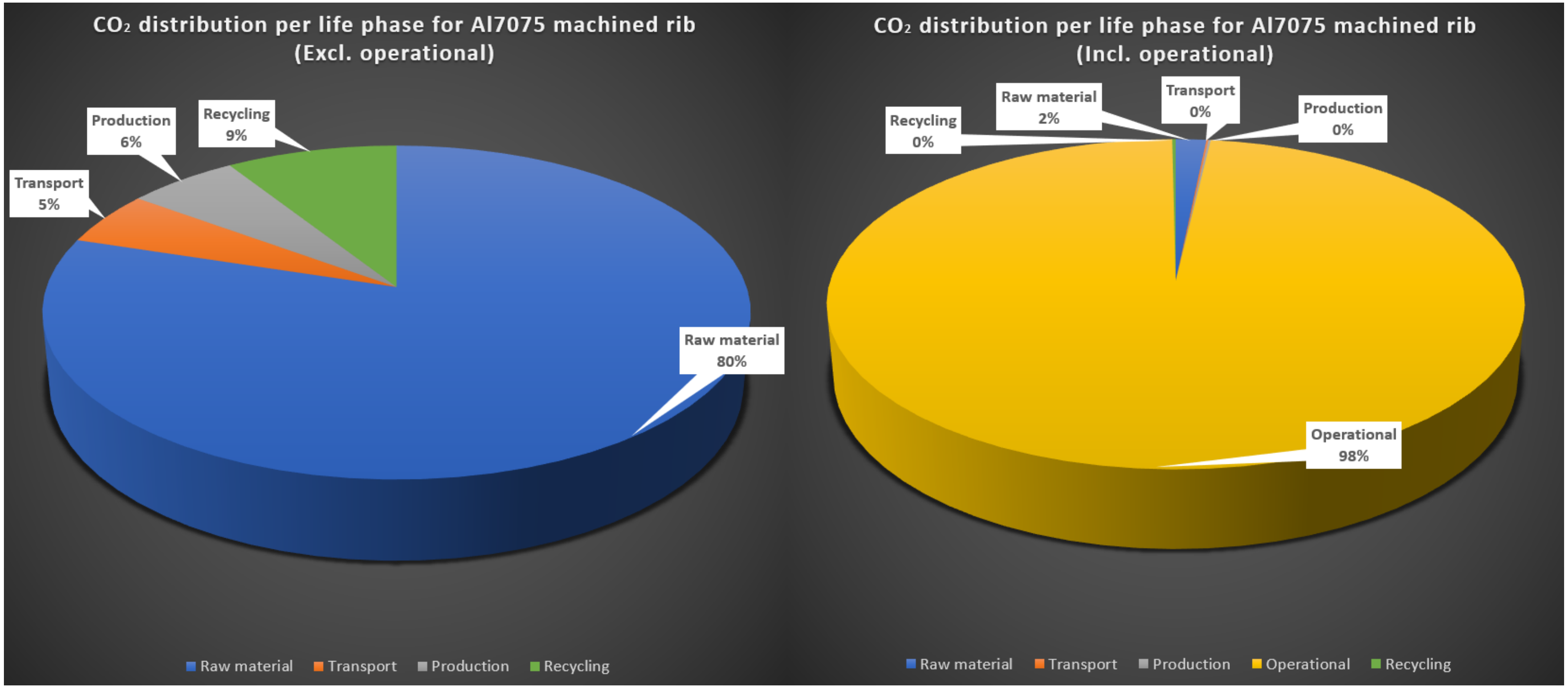


Figure 4.5: CO_2-eq distribution per life phase for Al7075 machined rib

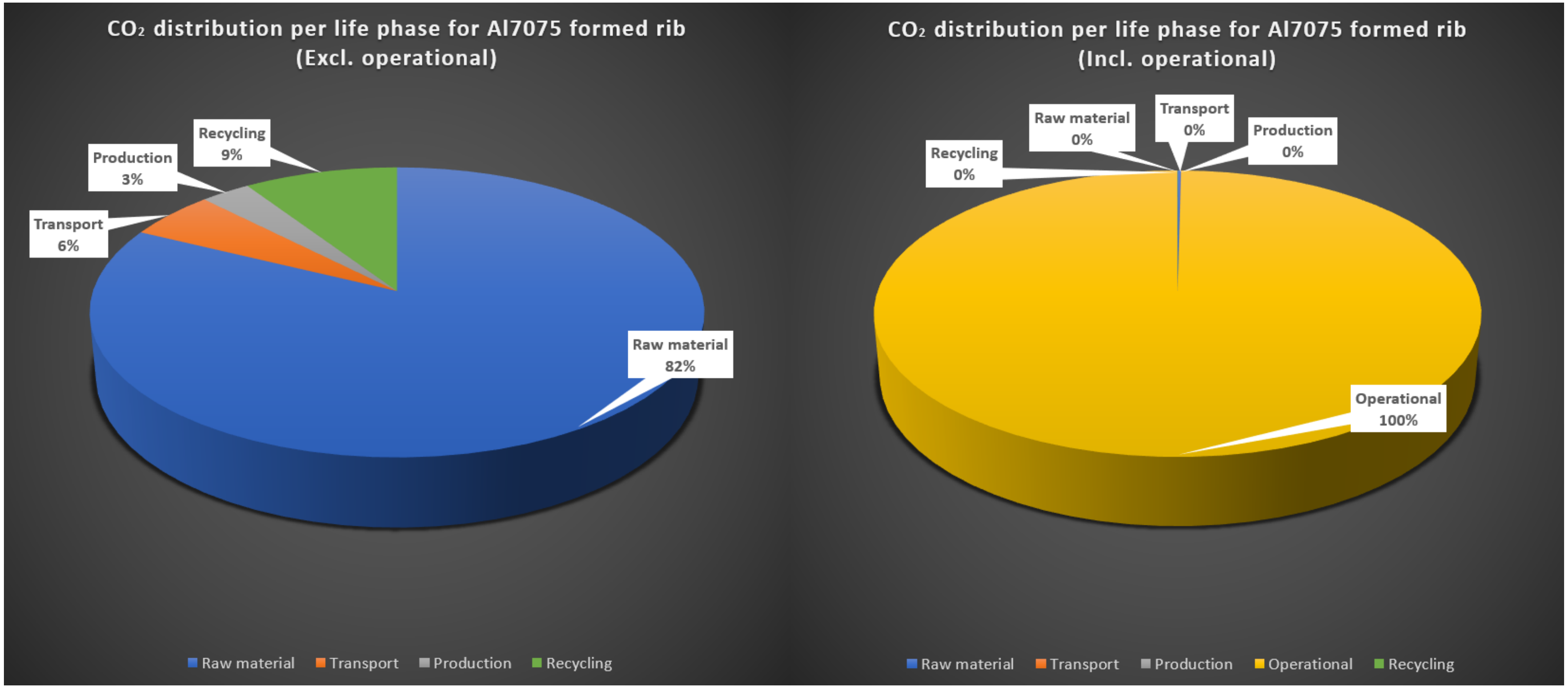


Figure 4.6: CO_2-eq distribution per life phase for Al7075 formed rib

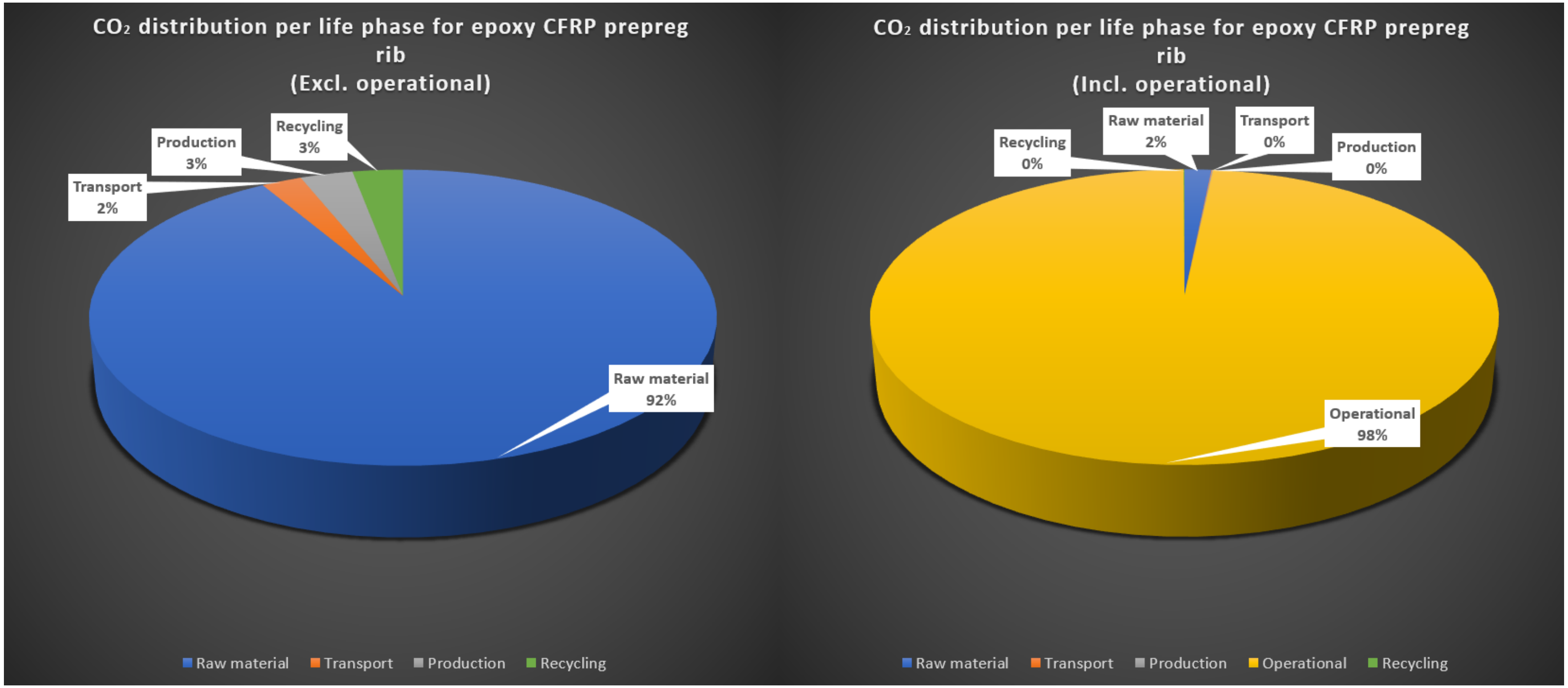


Figure 4.7: CO_2-eq distribution per life phase for epoxy CFRP prepreg rib

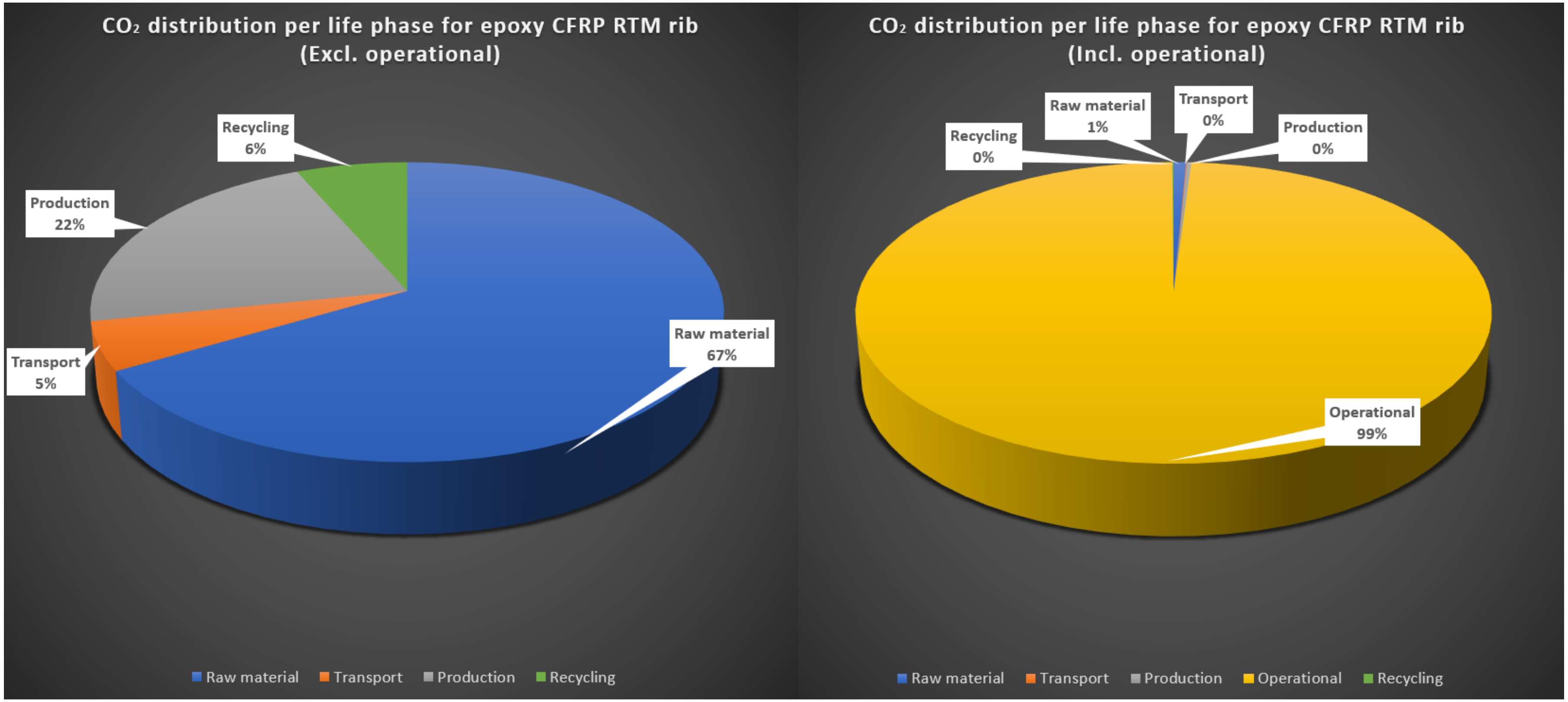


Figure 4.8: CO_2-eq distribution per life phase for epoxy CFRP RTM rib

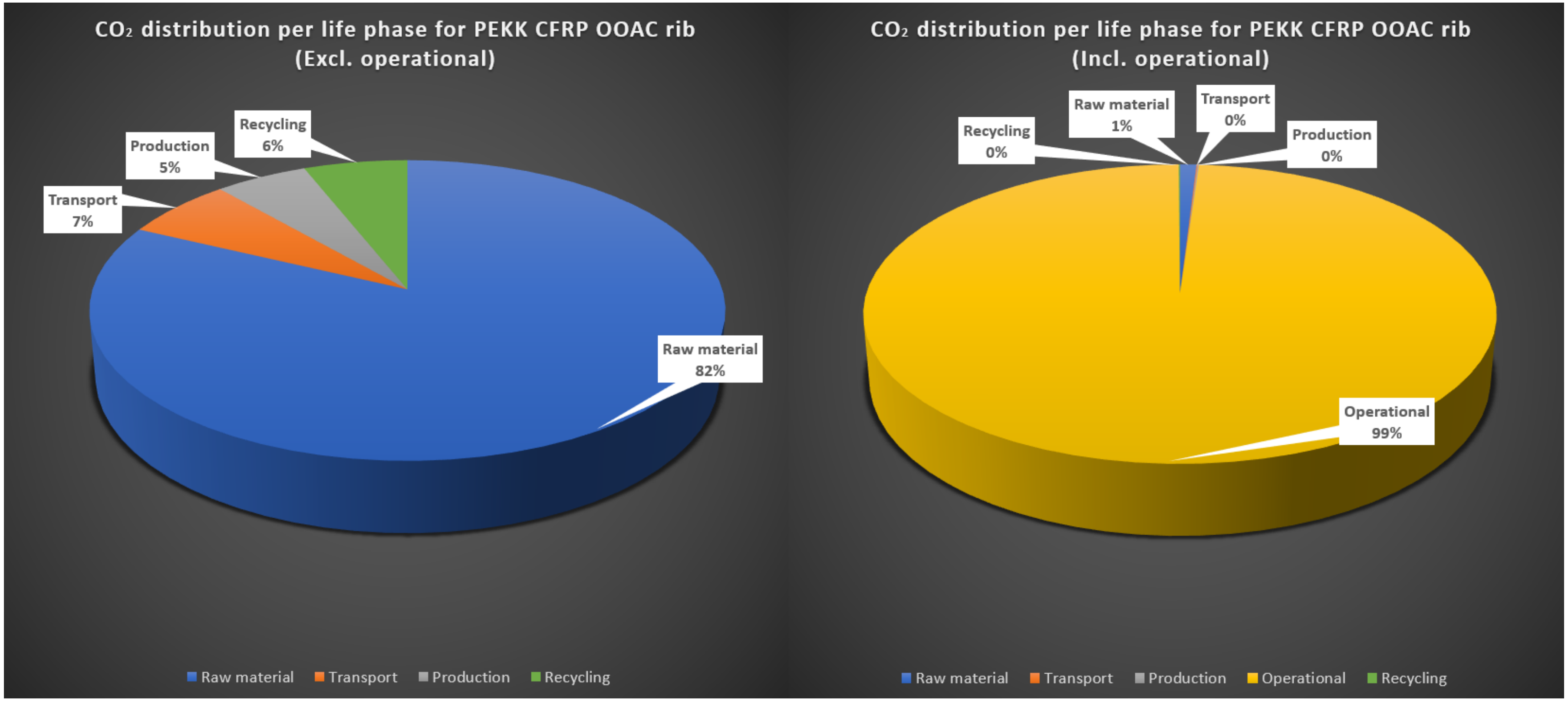


Figure 4.9: CO_2-eq distribution per life phase for PEKK CFRP OOAC rib

Sensitivity Analysis:
One aspect which is also considered for the discussion of the results is a sensitivity analysis for some of the assumptions made. As mentioned in the description of this chapter as well, a sensitivity analysis was conducted for some of the assumptions which have raised questions throughout the duration of this project, and on those which were considered important and with a potential of influencing the results.

The first element looked at was the use of adhesive bonds in the design of the sheet formed rib. In this case, it is known and has been mentioned in previous chapters that adhesive bonding is an uncommon technique for the situation at hand. Riveting is a more common alternative, however due to the assumptions of riveting using pneumatic tools, the power of which can not be estimated at this point in time, the energy consumption of such processes would have been negligible. Choosing adhesive bonding as a method on the other hand induced a certain amount of energy instead due to the cure cycles o the adhesives. The sensitivity analysis for this assumption aims to show this additional energy separately. Looking solely at the production energy (the stage in which adhesive bonding was considered), the energy without the use of this process would drop from 2.54$\cdot 10^3$ MJ to 2.23$\cdot 10^3$ MJ, or 12%. A similar percentage is seen for CO_2 where the emissions are reduced from 2.87$\cdot 10^2$ kg to 2.52$\cdot 10^2$ kg. In the bigger picture, these changes do not visibly affect the energy and CO_2 emissions for the entire life cycle of the components, since the total values as seen as well in Figure 4.1 and Figure 4.3 (numbers not including the operational phase) are much larger. If the operational phase is added to the mix as well, the change becomes entirely irrelevant.

The next assumption which was investigated was the storage time for the composites. This was done mostly out of curiosity of seeing the effect of shorter storage times on the life cycle. Currently, the assumption was that each thermoset material is stored for the full duration of its self life (18 months). Two additional calculations were conducted here, one for a storage time of 12 months and one for 6 months. For the 12 months and 6 months respectively, the energy was found to decrease from 74.1 MJ/batch to 49.4 MJ/batch and 24.7 MJ/batch (strictly for the storage energy). This is equivalent to decreases of 33% and 67%. On a larger scale, looking at the entire production stage, the changes are from 1.08$\cdot 10^4$ MJ to 1.08$\cdot 10^4$ MJ (thus essentially no change for 12 months) and 1.07$\cdot 10^4$ MJ (for 6 months). This shows a percent decrease of 0.1% when switching from 18 months to 6 months of storage, thus once again completely negligible. A similar analysis can be done for CO_2 emissions which show similar results.

The next element looked into required slightly more calculations. It has been assumed that the weights of the different composite components would be the same. In reality however, the two resins used (epoxy and PEKK) have different densities. This would of course result in different composite weights and in order to validate the assumption made, some calculations were done for this sensitivity analysis. It is known that the densities of the carbon fibre, epoxy and PEKK are $\rho_{CF} = 1840$ kg/m^3, $\rho_{epoxy} = 1400$ kg/m^3 and $\rho_{PEKK} = 1320$ kg/m^3 respectively. Additionally, the fibre fraction (by volume) was defined at 60%. Considering this, the following numbers will be used for the sensitivity analysis:

$f_{w_{epoxy}} = 0.6635$ Fibre fraction (by weight) for epoxy components
$r_{w_{epoxy}} = 0.3365$ Resin fraction (by weight) for epoxy components
$f_{w_{PEKK}} = 0.6765$ Fibre fraction (by weight) for PEKK components
$r_{w_{PEKK}} = 0.3235$ Resin fraction (by weight) for PEKK components

The geometry (and thus volume) of the components will still be considered constant between the different materials. The weight however due to the changed density will change, and the goal is to find the weight of the thermoset composites, since that of the thermoplastic composites (2.1 kg) was obtained by weighing the actual rib created by GKN Fokker. The following approach is thus taken:

$$V_{rib} = V_{resin} + V_{CF}$$
$$V_{rib} = \frac{m_{resin}}{\rho_{resin}} + \frac{m_{CF}}{\rho_{CF}}$$

Using the fact that the volume is constant, one obtains:

$$m_{EpoxyRib} \cdot \left(\frac{r_{w_{epoxy}}}{\rho_{epoxy}} + \frac{f_{w_{epoxy}}}{\rho_{CF}}\right) = m_{PEKKRib} \cdot \left(\frac{r_{w_{PEKK}}}{\rho_{PEKK}} + \frac{f_{w_{PEKK}}}{\rho_{CF}}\right)$$

Substituting the values presented earlier in this equation, one can find the ratio between the mass of the thermoset epoxy rib and the thermoplastic PEKK rib.

$$\frac{m_{EpoxyRib}}{m_{PEKKRib}} = 1.0196$$

This shows that the mass of the epoxy rib is only roughly 2% higher than that of the PEKK rib, and therefore there is no need for recalculation of the energies and CO_2 emissions from chapter 3 since the assumption that the two ribs will have the same weight is very close to reality.

Another aspect that could be looked at was the assumption that the painting processes (using pneumatic paint guns) consume a negligible amount of energy. While this is difficult to verify in the absence of measured data on the actual consumption at factory level, it is important to consider the original scope of this paper. This thesis aimed to generate a comparison between the different materials that could be used for a wing rib and their processing methods, from an environmental standpoint. Since the wing rib is assumed to have a constant geometry, regardless of the material chosen, and considering as well that the painting process is kept identical for all products, comparatively nothing will change between the different ribs, and therefore it was considered non-essential to verify this assumption further.

On the same note as the sensitivity analysis, the final check that can be done is also for the operational phase. While this is not the direct focus of this project, it is considered an interesting aspect to investigate for the future. Considering that the operational life is very long and that the energy consumption and CO_2 emissions during it are much higher than any of the other stages, it would be interesting to consider what would happen if alternative fuels would be used. In order to simulate this, some very basic calculations were considered here for an electric propulsion system and for a hydrogen one. In both cases, the energy required to move the aircraft components can be calculated the same way as before. In the case of an electric system, the energy would now be obtained from the electricity grid of the countries in which the aircraft is operating (as opposed to conventional fuels). Since the aircraft is likely to fly all over the world, the electricity mix conversion factor that should be used for this is 0.131 kg CO_2-eq/MJ of energy used. Considering that an electric engine is reported to have an approximate efficiency of 75%, and using the same calculations as in the case of conventional fuels, the specific energy of an electric engine is calculated at roughly $8.02 \cdot 10^{-4}$ MJ/(kg·km) compared to the $1.72 \cdot 10^{-5}$ MJ/(kg·km) used before. The CO_2 can also be calculated at $1.05 \cdot 10^{-4}$ kg/(kg·km) compared to the $1.24 \cdot 10^{-4}$ kg/(kg·km) obtained in the case of conventional fuels. The difference between the drop in energy requirements and the drop in CO_2 emissions is quite large, and this is due to the conversion factor used in conventional fuels (0.072 kg/MJ) which is smaller than the electricity mix one (0.131 kg/MJ). This suggests that for future applications the 0.072 kg/MJ factor might need to be modified. Additionally, for such a study the life cycle of the batteries would also need to be considered. For the hydrogen system, the estimations are more difficult to perform at this stage in the project. The CO_2 emissions during operation are known to be zero. Firstly, considering that the efficiency of such an engine will likely be around 35% similarly to what was seen for conventional engines, the calculations will remain mostly the same for the energy requirement. One will however have to consider the energy requirement for producing the hydrogen and as a result also the CO_2 emissions during its production. Since these energies were not considered however for the conventional fuels either, a fair comparison would be to look strictly at the operational energy and CO_2. The energy would theoretically remain the same, with the major impact being seen at the GHG emissions, where the yellow bars as seen in Figure 4.4 would decrease in the absence of CO_2.

For both of these technologies it is clear that from a GHG emissions point of view, the majority of emissions are generated either in the production of electricity for charging the batteries or in producing the hydrogen. Both of these processes currently use energy obtained from the electricity grid, which as discussed in chapter 1 is a mix of energy obtained from renewable sources but also fossil fuels and nuclear energy. An interesting point to consider would be the impact of switching entirely to green energy in the future. The short discussion on the source of the alternative fuels highlights once again one of the aspects mentioned in the case of general life cycle assessments, and that is the necessity of setting boundaries on the analysis performed. Tracing of the prime materials and processes may go back indefinitely. As such, while the operational phase could be defined as emission-free in the case of alternative fuels, in order for a vehicle to become truly emission-free, one must also ensure that the background processes are more sustainable.

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5
Conclusions and Recommendations

This thesis project started with two main goals. The first was to generate a preliminary tool for support in comparing the environmental sustainability of aerostructures built from different materials, both metallic and composite, and using different manufacturing routes for reaching the desired design. The second goal was to apply the data gathered in this context to a wing rib as a case study. The wing rib in discussion was rib number 14 within the Wing of Tomorrow project initiated by Airbus. The materials considered in this study were two aluminium alloys, Al7075 T73 and Al7050 T7451, a thermoset epoxy CFRP composite and a thermoplastic PEKK CFRP composite. For aluminium, the two manufacturing routes were machining and sheet metal forming, for thermoset composites one was manufacturing with prepregs and the second was RTM, while for thermoplastic out of autoclave consolidation (hot press consolidation) was chosen as the main manufacturing technology. Based on the results shown in chapter 4, an immediate conclusion is that manufacturing out of aluminium and using machining as a main technology is a costly option, mainly due to the really large amounts of material which ends up being removed from the starting blocks of aluminium during manufacturing. Additionally, despite of the good recyclability of the metal, the large amounts which need to undergo recycling will however still use relatively large amounts of energy and therefore have a high GWP, measured in emissions of CO_2-eq. While this energy is still much lower than what would be required if virgin aluminium would solely be used, the energy for large scale recycling is still significant. Despite the existence of alternatives such as sheet metal forming, which are at first glance more environmentally friendly, it is important to note the operational requirements of the different components that are manufactured. For the wing rib, while the process rendered the least amount of energy required and also the lowest CO_2 emissions, the limitation mentioned in previous sections too regarding the thicknesses achievable through sheet forming and the complexity of the parts as well impact the use of the rib in some applications, and therefore the environmental sustainability advantage loses some of its importance.

From the list of composites, it was seen that variations exist in the energy requirements and CO_2 emissions between manufacturing technologies as well. For all of these composite manufacturing technologies however, the numbers appear to be significantly smaller in the production phase than for their machined aluminium counterparts, thus indicating a great potential for the future. In particular, looking at the thermoset RTM composite, this presents the second lowest numbers after sheet formed aluminium. These results could be attributed to the high amounts of material that are required when it comes to processes such as machining of aluminium. Here, despite the relatively low energy cost compared to composites (roughly 200 MJ/kg for aluminium alloys vs in excess of 600 MJ/kg for composites), the sheer amount of raw material which needs to be produced for one rib (poor buy to fly ratio) simply overshadows the specific energy consumption advantage. Additionally, the composites presented a significant advantage in the long run due to their lower weights. For a comparison of the initial life phases for each material (raw material manufacturing and production), as well as the end of life phase, the operational stage was removed. When this is added to the mix in order to compare the entire life cycle of the materials however, composites showed a significant advantage compared to metals still, simply through their reduced weight which required less energy and thus generated less CO_2 emissions, by roughly 42%. Regarding the sensitivity analysis which was conducted using the results, it was seen that some of the assumptions which were originally thought to have potential of impacting the results, were in fact negligible. This included the neglected weight differences between different composite materials (in reality with a weight difference of roughly 2%), the use of adhesives for bonding the structures (with a negligible amount of energy being added to the life cycle overall), and the storage times for thermoset components (where a decrease in time of up to 67% would only result in an energy decrease of 0.1% for the production stage). Lastly the sensitivity analysis contained as well a discussion of whether alternative propulsion systems could be used in the future to reduce the operational phase energy and CO_2-eq emissions. Here, it was seen, at least on a qualitative level, switching from conventional fuels to electric or hydrogen propulsion systems could significantly improve sustainability by removing the CO_2 and therefore reducing the total amount of emissions seen in Figure 4.4. Yet, this only partly fixes the issues, since in order to achieve a fully sustainable transportation, the background energy sources would need to be converted to green energy sources as well, as opposed to the current mix between fossil fuels, renewable and nuclear sources that are used nowadays. Due to all of these, at the moment, the changes in fuels would generate immediate results which are highly visible by removing a large part of the emissions (consider however that the energy requirements would not change). While modifications and optimisations in the materials and processing options do generate improvements overall as well, due to the large amounts of emissions during operations, these structural changes are not immediately visible unless the operational phase is separated.

Moving onto the recommendations for future work, this study has been conducted with the use of various databases and a combination of primary and secondary data for the different processes involved in the part manufacturing stages, as well as the other stages of the parts' life cycle. In order to do so, numerous assumptions had to be made and they were documented accordingly, aiming to improve traceability and aid in further improving the results with future iterations. In particular, the findings of this study could be further improved by the in-depth study of individual life stages and individual processes, and by conducting practical work and creating prototypes of required parts, such that primary data is available for the analysis at all steps. This would reduce the necessity of relying on external data and also remove a number of assumptions, thus bringing the result closer to the actual numbers (and especially closer to the numbers obtainable locally at GKN Fokker Hoogeveen, or other manufacturing areas for the ribs). Some of these elements were also visible when performing the sensitivity analysis. One example includes the use of pneumatic tools throughout the manufacturing stage. Here, these have been considered negligible, especially considering the numbers found for energy consumption and GHG emissions for the other processes around them. In reality, a certain amount of energy will be used, especially since these tools are powered by large compressors at factory level. The percentage of energy used only by tools such as paint guns or rivet guns (if mechanical assembly is considered), on the factory level should be estimated, which would allow for an energy estimation to be made based on the total power consumption of the compressors. For comparison purposes, this will not make a difference between the different ribs considered as mentioned before, mostly since all of the painting processes were considered to be identical and therefore any change brought to one part will automatically be applied to the others too. Considering this energy however will give a better impression of the total effect on the environment and the sustainability of the processes (although, based on the numbers seen in this study for larger processes, it is expected that the impact of painting and assembly processes using pneumatic tools will remain negligible). While on the topic of improvements based on the sensitivity analysis results, another important aspect that was found was the conversion factor used for converting energy to emissions of CO_2 in the operational phase. While databases provided the number for conventional fuels to be 0.072 kg/MJ regardless of the type of transport considered, it was observed during the sensitivity analysis that switching to electric propulsion would require the use of a conversion factor of 0.131 kg/MJ, resulting from the world electricity mix. Since this mix is obtained by using a weighted average of fossil fuels, renewable sources and nuclear energy, it appears peculiar that the emissions obtained strictly from conventional fuels would be lower. These numbers would therefore be important to study in more detail. Of course, a further study into the alternative fuels discussed, where more quantitative data can be provided could make the subject of another project on sustainability for these structures. Additionally, improvements can be made as well by considering other elements of sustainability such as waste generated and consumables. Since this element was only briefly mentioned in this thesis, an in-depth understanding of the amounts of waste (of any nature), and their disposal would be required in order to have a more complete picture of the environmental impact of these structures. On the same note, as mentioned in the introduction, two other pillars in sustainability are the economical and social sustainability. While these are not directly connected to the topic of this thesis, in order to fully understand whether large scale manufacturing of a part can be done, these two elements may have to be considered in other individual studies as well.

Lastly, two more recommendations will be made. The first one is regarding the processes which require heat energy throughout the manufacturing of the wing ribs since it was seen throughout the project that such processes were generally high energy consumers, and that they would make up a large part of the total manufacturing energy. If one was to aim for further improvement of the manufacturing of ribs, these processes could be an important starting point. The final recommendation is with regards to some of the assumptions made for this thesis when it comes to values used from databases. It was considered for the case at hand that the highest values from a range will be used in order to ensure that the result remains conservative. This of course has an impact on the end result and a recommendation would be to also consider alternative ways of selecting data, such as taking the middle of an interval or in some cases the least conservative values of the interval in order to see the effect on the results. The other assumption which might need to be checked for future studies is the one about the geometry of the different ribs. For the study at hand it was assumed that both the composite and the metallic ribs will have the same geometry which of course in reality is not the case. This will affect the amount of energy that goes into the processes for manufacturing these ribs, but also the emissions during the operational phase since the weight of the ribs is likely to change with a change in geometry.

To conclude this study, the results of this project suggest that switching to composite structures could positively impact the future of air travel, since in the long run, due to the long operating life of an aircraft the lower weight of these structures will result in a lower environmental impact. Additionally, with the emergence of thermoplastic materials in the industry, the impact on the environment could decrease even further. Due to their recyclability (only into structures of lower structural importance), these could reduce the overall energy consumption and CO_2 emissions, although not immediately with the main structural components they are used for, but for potentially countless future applications.

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A

Assumptions Made

Assumption list

- *When ranges are provided for data sets, the most conservative values should be taken for the calculations to ensure a conservative result.*
- *When process energy is involved and the country energy mix is required, the CO_2 footprint conversion factor used will be for the whole region rather than the individual country (e.g. Europe instead of France, or North America instead of Canada).*
  [Chapter 2, pages 20-21 (Raw material production - machined aluminium)]

- *When transport energy is concerned, the CO_2 footprint conversion factor used is 0.072 as provided in the database of CES EduPack for transport energy.*
  [Chapter 2, page 21 (Transport - machined aluminium)]

- *The oven for drying the parts during NDI steps has a capacity of 1 m^3.*
- *Air density at sea level is 1.225 kg/m^3.*
- *Specific heat capacity of air at constant volume is 0.718 kJ/(kg·K).*
- *Room temperature of 20°C.*
- *Furnace used at full power for heating stage.*
- *The refractory bricks used are Helios R 65SA 230x114x64 mm.*
- *Specific heat capacity of refractory bricks is 1.2 kJ/(kg·K).*
- *Paint guns use a negligible amount of energy.*
  [Chapter 2, page 23 (Part manufacturing - machined aluminium)]

- *All aluminium components are recycled into same quality aluminium material.*
  [Chapter 2, page 24 (End of life - machined aluminium)]

- *Al7075 T73 and Al7050 T7451 can be used for sheet forming processes in the context of this thesis.*
  [Chapter 2, page 26 (Raw material production - aluminium sheet metal forming)]

- *Energy of forming processes is negligible by comparison to heating processes further down the line.*
  [Chapter 2, page 27 (Part manufacturing - aluminium sheet metal forming)]

Assumption list

- *For curing the adhesive, a similar oven to that used for NDI is considered*.
- *Epoxy adhesives are used for adhesive bonding*.
- *A cure temperature of 120 degrees is chosen for the adhesive*.
[Chapter 2, page 28 (Part manufacturing - aluminium sheet metal forming)]

- *The thermoset laminate is a [0/+45/-45/90]s quasi-isotropic layup using high strength carbon fibre with fibre fraction volume between 0.55 and 0.65.*
- *Autoclave curing between 115-180°C, 6-7 bar.*
[Chapter 2, page 30 (Raw material production - Epoxy-CFRP Prepreg)]

- *Maximum energy consumption of a freezer per month is of roughly 54.08 kWh (194.688 MJ).*
- *The refrigeration time for thermoset composites is of 18 months.*
- *For thermoset composites, thawing occurs at room temperature with no energy input, and thawing is performed only once.*
- *Robots used in the ATL and AFP processes use a negligible amount of energy.*
- *Cutting and trimming are done with the same machine and therefore the total energy use will be bundled in one stage only (cutting).*
- *Scanning time for ultrasonic testing increases linearly with part surface area.*
- *A scan machinery is similar to C scan machinery, and scanning times are similar for equally sized parts.*
[Chapter 2, pages 31-33 (Part manufacturing - Epoxy-CFRP Prepreg)]

- *In the case of combustion of materials, the CO_2-eq are taken directly from the database since these processes are producers of energy rather than consumers as for other processes described.*
[Chapter 2, page 34 (End of life - Epoxy-CFRP Prepreg)]

- *In the RTM processing, the preforming energy is taken from the EduPack database for the quasi-isotropic prepreg selected previously.*
[Chapter 2, page 35 (Part manufacturing - Epoxy-CFRP RTM)]

- *Usually, for automated processes (ATL/AFP), cutting is included in the process and could be passed as negligible for energy consumption. For this project, cutting is however clustered with final trimming of the part and therefore the energy consumption is considered separately from layup.*
[Chapter 2, page 37 (Part manufacturing - PEKK-CFRP OOAC)]

- *Both the aluminium and the CFRP ribs will have the same geometry.*
- *NDI preparation (degreasing) for metals takes the same amount of parts at once as the drying stage prior to the inspection.*
[Chapter 3, pages 44-45 (Inventory analysis - machined aluminium]

- *For the sheet formed rib, the stiffener design is unknown. Processing energy assumed negligible.*
- *For the sheet formed rib, cold rolling is used.*
- *Cutting for all ribs is done with mechanical cutting and takes roughly 30 minutes per part, and that includes the trimming required after the main processing steps.*
[Chapter 3, pages 51-53 (Inventory analysis - aluminium sheet metal forming]

Assumption list

- *All composite versions of the wing rib have the same weight.*
  [Chapter 3, page 57 (Inventory analysis - Epoxy-CFRP prepreg]

- *The composite's fibre fraction volume is 60%.*
- *RTM infusion time for one rib is considered to be 1 hour.*
  [Chapter 3, pages 64-65 (Inventory analysis - Epoxy-CFRP RTM]