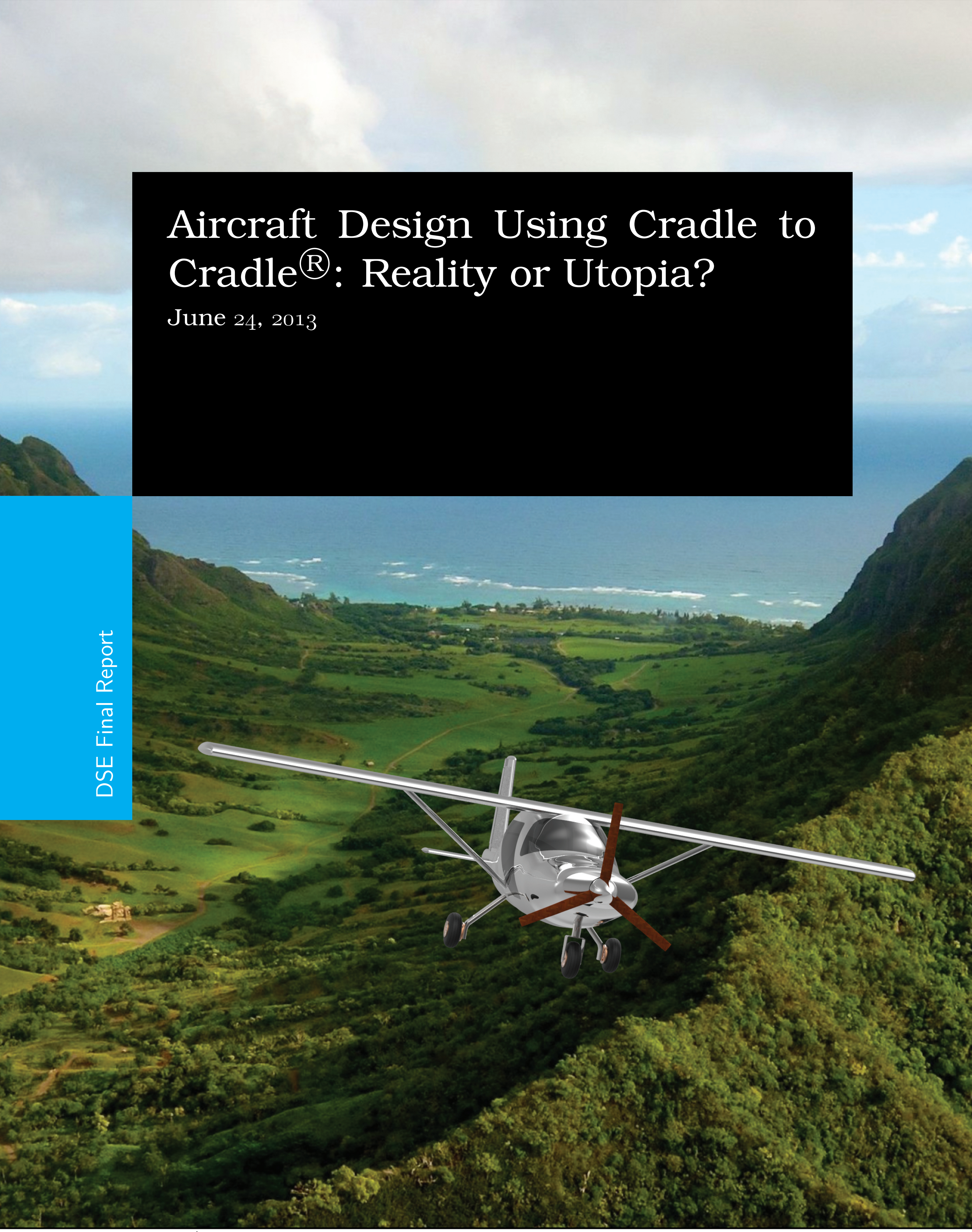

Aircraft Design Using Cradle to Cradle®: Reality or Utopia?

June 24, 2013

DSE Final Report

Faculty of Aerospace Engineering

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Preface

This report is submitted for the AE3200 Design Synthesis Exercise at the Delft University of Technology. In this final report, the following question will be answered: "*aircraft design using Cradle to Cradle®: reality or utopia?*" The answer to this question will be given by focussing on a aircraft sizing, structural analysis, power & performance analysis and a business model of the design.
This project, which has been conducted and completed within eleven weeks, is a good example of cooperative endeavour among a number of students. It is a good opportunity to deepen our interests in the sustainable problems which are prominent these days.
This will be the last step before achieving a Bachelor's degree in Aerospace Engineering.

A great deal of help and support has been given to us during the process of this project. We would therefore like to give our deepest gratitude to the following people: tutor MSc Ronald van Gent for his guidance during the project, coaches D.Eng. Martin Ruess & D.Eng. Irene Fernandez Villegas for supporting us throughout the research and offering their help. D.Eng. Erik Tempelman & MSc. Bram van der Grinten for sharing their experience about Cradle to Cradle® & automotive design. D.Eng. Calvin Rans, MSc. Jos Sinke, D.Eng. René Alderliesten & Prof. D.Eng. Rinze Benedictus for providing us with the required information to analyse the structure of our design. Last but not least we would like to give our deepest gratitude to the chairman of AELS (Aircraft End-of-Life Solutions), Derk-Jan van Heerden, for sharing his experience on the recycling of aircraft and providing us with valuable suggestions for the end-of-life of our design.

Summary

A sustainable approach towards the environment is an important element in society to guarantee sufficient resources and acceptable living conditions for each individual. Inspired by Michael Braungart and William McDonough, the Cradle to Cradle® principle focusses on the elimination of waste and the removal of negative environmental impacts of today's products.
The project objective is to analyse the feasibility of designing a two-seater Cradle to Cradle® aircraft for the general aviation market. A set of three trade-offs has been executed in order to select the final concept which would enter the preliminary design phase. Once this concept was chosen, the overall design of the aircraft has been divided into four major subgroups: sizing, power and propulsion, structures and materials and the business case.

Sizing of the aircraft started with the wing and engine. A wing and power loading diagram was constructed to find important wing and engine design parameters. From this a wing surface of 10.4 m^2 and a required engine power of 103 hp was obtained. Next, a weight estimation was performed. A baseline weight estimation was set for further design analyses. An operative empty weight of 393 kg and a maximum take-off weight of 716 kg was found. After the weight estimation, the aircraft's empennage was sized in a stability and control analysis. Centre of gravity ranges and limits were determined. Finally, a standard mechanical control system was implemented in the design, using steel cables.

For the propulsion system, ethanol E100 was chosen as fuel. One of the main reasons for this was its high availability: ethanol is easily made from various biological sources such as switchgrass, sugercane, corn or waste. Also, ethanol can be made relatively cheap and operational costs can be reduced due to a lower strain on the engine by a cooler burning process. A downside is the lower energy density, which leads to a heavier fuel load. This is partially compensated by a higher engine efficiency. A Rotax 912ULS engine is used, which is able to generate 103 hp running on ethanol at an efficiency of approximately 0,40. In total, 97 % of the engine can be recycled according to the Cradle to Cradle® principle. Furthermore, a three blade propeller was chosen which gives the aircraft a far field noise of 60.4 dB.
The structures and materials part focused specifically on three main aspects: the material selection, the structural design and the end-of-life possibilities. In an early stage of the project, automotive alloys where identified to be used for the structural design. The Al-6022 alloy has been identified to be the most suitable for the aircraft's structure. The aircraft's structure was designed according to the semi-monocoque principle where welding, bolting and riveting are used for joining. Those rivets will be made from the Al-6022 alloy as well, which enhances the end-of-life possibilities. From the end-of-life plan, the conclusion was made that 93 % of the aircraft's operating empty weight can be recycled of which 89 % according to the Cradle to Cradle® principle. Aluminium, steel and the interior provide the best recycling possibilities while coatings and tyres are the most difficult parts to be recycled.

For the business plan a lease construction has been established. This is done in order to make sure that the aircraft is returned at end-of-life. The customer may choose different contract durations. For each contract the operational costs (maintenance, fuel, parking, insurance) add up to $ 77.37 per hour. The wet lease prices (including dry lease, maintenance and insurance) for the 8, 10 and 15 year contracts are $ 102.54, $ 92.85 and $ 80.18, respectively. Finally, the total cost of ownership (including wet lease and landing fees) for the 8, 10 and 15 year contracts are $ 152.41, $ 142.72 and $ 130.05, respectively.

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List of Abbreviations

Abbreviation	Description
100LL	Low Lead Fuel Type
Al	Aluminium
A/C	Aircraft
ADP	Abiotic Depletion Potential
AELS	Aircraft End-of-Life Solutions
AFRA	Aircraft Fleet Recycling Association
Al	Aluminium
AN	Airforce Navy Specifications
AOPA	Aircraft Owners and Pilots Association
API	Air-conditioning, Pressurisation, De-icing system
Avgas	Aviation gasoline
BOS	Basic Oxygen Steelmaking
BPA	Bisphenol A
C2C	Cradle to Cradle®
CO_2	Carbon Dioxide
CH_4	Methane
CS	Certification Specifications
Cg	Centre of Gravity
DCF	Discounted Cash Flow
DMA	Dynamic Mechanical Analysis
DSE	Design Synthesis Exercise
E85	85% bio-ethanol
E100	100% bio-ethanol
EADS	European Aeronautic Defence and Space Company
EAF	Electric Air Furnace
EASA	European Aviation Safety Agency
ELT	Emergency Locator Transmitter
EOL	End-of-Life
EP	Eutrophication Potential
EPEA	Environmental Protection and Encouragement Agency
ETP	Eco-toxicity Potential
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FBS	Functional Breakdown Structure
FSW	Friction Stir Welding
GHG	Greenhouse Gas
GPS	Global Positioning System
GWP	Global Warming Potential
HAM	Harmful Air Pollutants
H_2O_2	Hydrogen Peroxide
HTP	Human Toxicity
IAE	Instrumentation, Avionics and Electronics
IFSD	In-Flight Shut Down
INM	Integrated Noise Model
LC	Life Cycle
LCA	Life Cycle Analysis
LED	Light Emitting Diode
LFG	Landfill Gases
MAC	Mean Aerodynamic Chord
MIT	Massachusetts Institute of Technology

Abbreviation	Description
mPPE	Modified Polyphenylene
MSW	Multi Solid Waste
MTOW	Maximum Take-off Weight
NASA	National Aeronautics and Space Administration
NACA	National Advisory Committee for Aeronautics
NPG+	Non-Aqueous Propylene Glycol
ODP	Ozon Layer Depletion Potential
OEW	Operation Empty Weight
PAMELA	Process for Advanced Management of End of Life Aircraft
PC	Polycarbonate
PEEK	Polyetheretherketone
PEI	Polyetherimide
PLB	Personal Locator Beacon
POCP	Photochemical Oxidation Potential
PPS	Polyphenylene sulfide
PU	Polyurethane
PVC	Polyvinyl Chloride
RDTE	Research, Development, Test and Evaluation
RR	Recycling Rate
RSW	Resistance Spot Welding
SI	Systeme International
TBO	Time Before Overhaul
T/O	Take-off
TOP	Take-off Parameter
TP	Toxicity Potential
TPC	Thermoplastic Composite
USA	United States of America
USD	United States Dollar
V&V	Verification and Validation
VLA	Very Light Aircraft
VOC	Volatile Organic Compound
WEEE	Waste Electrical and Electronic Equipment

List of Symbols

Symbol	Description	Unit
Γ_0	Lifting line theory circulation	$[m^2/s]$
η_p	Propeller efficiency	$[-]$
ρ	Density	$[kg/m^3]$
σ	Bending stress	$[Pa]$
σ_m	Mean fatigue stress	$[Pa]$
σ_Y	Von Mises stress	$[Pa]$
τ	Shear flow	(N/m)
A_{xx}	Aera of part XX	$[m^2]$
AR	Wing aspect ratio	$[-]$
b	Wing span	$[m]$
c	Chord length	$[m]$
$\bar{c}$	Mean aerodynamic chord length	$[m]$
cr	Climb rate	$[m/s]$
c/V	Climb gradient	$[-]$
C_D	Drag coefficient	$[-]$
C_{D_0}	Drag coefficient (speed independent)	$[-]$
C_{ACQ}	Acquisition Cost	(e)
C_L	Lift coefficient	$[-]$
C_{L_α}	Slope of the lift curve	$[-/rad]$
$C_{L_{A-h}}$	Aircraft tailless lift coefficient	$[-/rad]$
$C_{L_{\alpha_h}}$	Slope of the lift curve of the horizontal tail	$[-/rad]$
$C_{L_{clean}}$	Clean lift coefficient	$[-]$
$C_{L_{landing}}$	Landing lift coefficient	$[-]$
$C_{L_{max}}$	Maximum lift coefficient	$[-]$
$C_{L_{TO}}$	Take-off lift coefficient	$[-]$
$c_{m_{ac}}$	Moment coefficient around the aerodynamic center	$[-]$
C_{OPS}	Operating Cost	(e)
C_{PIS}	Disassembly Cost	(e)
$d\epsilon/d\alpha$	Wing down wash coefficient	$[-]$
e	Oswald efficiency factor	$[-]$
f	Ratio take-off and landing weight	$[-]$
F_{XX}	Force of component XX	$[N]$
F_{Cr}	Buckling force	$[N]$
g	Gravitational acceleration (9.81)	$[m/s^2]$
h	Wing box height	$[m]$
I_{xx}	Moment of inertia	$[m^4]$
K	Gust intensity factor	$[-]$
K_{1c}	Fracture Toughness	$(MPA\sqrt{m})$
l_h	Distance between wing and tail	$[m]$
L	Lift	$[N]$
M	Moment	$[Nm]$
m_{xx}	Mass of component xx	$[kg]$
n	Load factor	$[-]$
n_{min}	Minimum load factor	$[-]$
n_{max}	Maximum load factor	$[-]$
n_{ult}	Ultimate load factor	$[-]$
p	Pressure	$[Pa]$
P_{TO}	Take-off power	$[hp]$

Symbol	Description	Unit
q	Distributed loading	$[N/m]$
q_s	Shear flow	$[N/m]$
q_{b_i}	Shear flow in section i	$[N/m]$
R	Fatigue stress ratio	$[-]$
R_{EOL}	Revenue from selling EOL materials	[$]
S	Surface area	$[m^2]$
S_{wet}	Wet surface area	$[m^2]$
S_h	Horizontal tail surface	$[m^2]$
t_{skin}	Skin thickness	$[m]$
T	Thrust force	$[N]$
TOP	Take-off parameter	$[-]$
$\hat{u}$	Statistical gust speed	$[m/s]$
V	Shear force	$[N]$
V	Airspeed	$[m/s]$
V_h	Velocity at the horizontal tail	$[m/s]$
V_h	Manoeuvre speed at negative load factor	$[m/s]$
V_a	Manoeuvre speed	$[m/s]$
V_b	Maximum intensity gust speed	$[m/s]$
V_c	Cruise speed	$[m/s]$
V_d	Dive speed	$[m/s]$
V_{stall}	Stall airspeed	$[m/s]$
V_{TO}	Take-off airspeed	$[m/s]$
W_{XX}	Weight of component XX	$[N]$
W/S	Wing loading	$[N/m^2]$
W/P	Power loading	$[N/W]$
$\bar{x}_{cg}$	Center of gravity position	$[m]$
Z_{xx}	Z-coordinate of element XX	$[m]$

PART I

INTRODUCTION

“The world will not evolve past its current state of crisis by using the same thinking that created the situation”

Albert Einstein,

Theoretical physicist, Nobel Prize winner in 1921

Chapter 1 | Problem Description

Albert Einstein:" *The world will not evolve past its current state of crisis by using the same thinking that created the situation.*" Even 60 years ago it was already known that the current way of thinking is not the one we should keep following. But after more than 60 years humans still think in an old fashioned way. People only think about now and not about the future, which will eventually lead to world wide disasters. Today the first signs of the changing world can already be noticed - hurricanes in the USA, food shortages due to drought, floodings in Europe, etc. Natural disasters are striking us in a pace that is never seen before and people are getting more conscious about climate change. This started a 'new' way of thinking which is based on: let's make it less worse! However, this is not going to change the world. It can be seen that even with this philosophy the ecological impact of human beings is not decreasing. It is in fact even increasing and it does not seem to get better with this way of thinking. In the last 100 years, the average global temperature went up with almost one degree Celsius (see figure 1.1) and the amount of waste produced by humans has been increasing significantly; in Denmark with 40 % during the last 20 years (see figure 1.2).

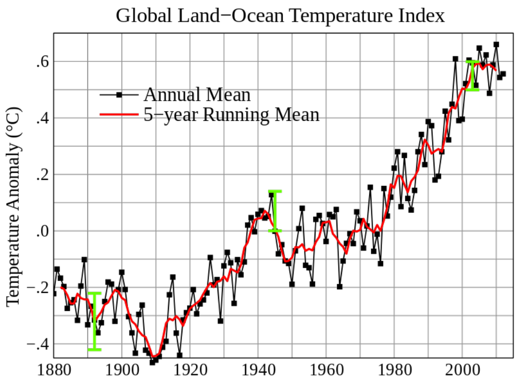

Figure 1.1: Evolution of the temperature on Earth [1]

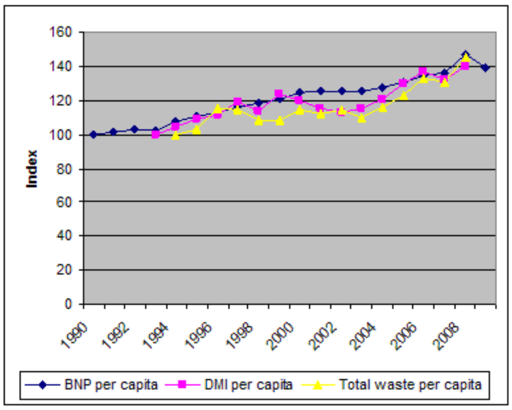

Figure 1.2: Waste production evolution in Denmark [2]

One of the reasons why this is not getting better while people do their best to improve is because people think they are recycling, while they are actually downcycling. The products that are recycled, eventually end in a landfill because the quality decreases every time they are recycled. This decrease in quality means the products can not be used forever and thus they are downcycled. It is known that the society of today is too much focused on "the possession" of goods instead of "the use" of a product. The problem with this reasoning is that people do not look at the future of a product and just throw it away without thinking about the possible consequences. This creates an enormous waste problem, which needs to be solved. This waste has a huge ecological impact and if people do not start to keep this in mind, the consequences will be disastrous.

A new change needs to be made: *"Do not make the world less worse but make it good!"* Do not downcycle products, but make sure they can be used forever. A product may not have an impact on the future, so after its life it should be dismantled and used again without a decrease in quality. If the quality does not decrease and the production process does not have an influence on the environment, the product can be classified as a good product, without an impact on the future. Only if people adapt and live according to this new philosophy, the world will be able to continue in the state it is now and stop hurricanes in the USA, food shortage due to drought, floodings in Europe, etc. And this is where this report is about.

Nowadays, some new philosophies are getting developed. These philosophies try to change the general way of thinking of human beings, so our world will be capable of handling so many people in a way that is good for everyone. One of these philosophies is Cradle to Cradle® [3]. In general, the basic three principles are: waste equals food, celebrate diversity and use the current solar income. However, the detailed explanation can be found in chapter 2. This report will strive to implement this philosophy in the following ways:

- Inspire other manufacturers: This report wants to be innovative and inspire other people to use this philosophy. This is necessary because everybody needs to change before the ecological impact of humans can be reduced.

This report focuses of course on general aviation but the philosophy can be used in different fields.

- Reduce ecological impact: During the whole design process, reducing the ecological impact was a key factor; as well for the materials that are used as for the fuel to power the aircraft. Reducing waste and CO_2 emissions was the highest priority during the design.
- Change in mindset: The report wants to change the mindset of people and introduce a new way of thinking. People need to realise they can not keep living like they are today. That is the reason why this culture needs to change from "I have ..." to "I use...". This change will make sure that the people of today won't have an impact on future generations.
- Economical benefits: the above adaptions need to fit in a good business plan. Nowadays, people can only be convinced if they can save money. This is why it is so important to make sure this whole new way of thinking is actually an economical benefit. Also this was kept in mind during the design of the Cradle to Cradle® aircraft.

Transportation is becoming one of the most important factors in human life which is why a major change needs to occur here. Nowadays, mainly fossil fuels are used but this imposes some major problems. Burning fossil fuels emits CO_2 which causes global warming. Now, transportation is getting available for more and more people, which will only cause the effect of global warming to increase. Also, fossil fuel resources are not infinite. In a certain amount of time, on which scientists cannot agree, all fossil fuels sources will deplete (see figure 1.3). That is why a major change needs to be implemented now, such that renewable fuels can be spread over the world before no more fossil fuels can be found.

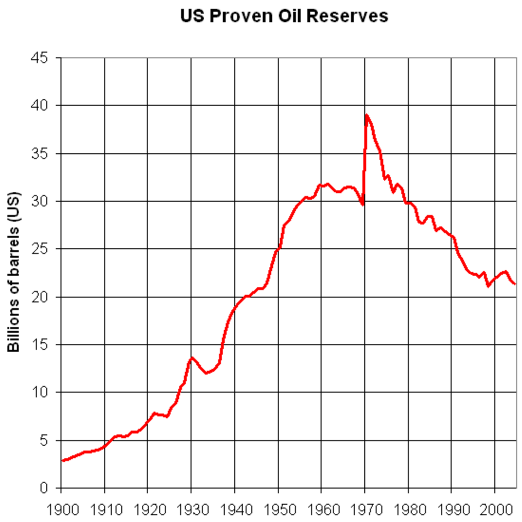

Figure 1.3: Proven oil reserves in the USA [4]

Now the Cradle to Cradle® aircraft copes with all these problems. It is designed to decrease the impact on the environment by using renewable fuels and the waste management is taken into account during the development, so it will not have an impact on future generations. After its designed life it can be almost fully recycled and a new aircraft will be made from the same material. This will be possible because of the use of new techniques, new materials and new fuels. Also the disassembly will be fully integrated in the design. This unique features will definitely have a positive impact on the ecological impact of air transportation on this world. This report will give an overview of the development of the Cradle to Cradle® aircraft , an aircraft built following the principles of Cradle to Cradle®.

The Cradle to Cradle® aircraft is called InfiniCraft. The name is an aggregation of two words: Infinitum and Aircraft. The word Infinitum is Latin for infinity. The reference to infinity is made, because the lifespan of the aircraft is essentially infinite. The materials can be recycled to make the aircraft over and over again (Cradle to Cradle®). The logo as shown in figure 1.4 represents the life cycle of the aircraft. The aircraft miniature in the logo shows the contour of the InfiniCraft.

Figure 1.4: Logo InfiniCraft

In the report, the whole design process of the InfiniCraft will be described. The report consists of six major parts. In part I a recap of the previous reports will be given. First, in In chapter 2 the Cradle to Cradle® philosophy will be described. In chapter 3 the requirements for the project are described. Furthermore, in chapter 4 and 5 the functional flow and breakdown will be showed and explained. In chapter 6 the N^2 chart (a tool to identify relations between design parameters) will be presented and all the relations between the functional units will be given. Finally, in chapter 7 a recap of the trade-offs from the midterm report will be given.

In part II the sizing of the aircraft will be explained. First, in chapter 8, the initial sizing of the airplane will be explained, while in chapter 9 the class II weight estimation will be given. Afterwards, in chapter 10, the stability and control of the aircraft will be investigated. In chapter 11, the dimensions of the aircraft will be described. Finally in chapter 12, the control systems will be designed.

Than, part III will deal with the propulsion system of the aircraft. First, in chapter 13 the fuel selection will be described quickly. In chapter 14 the life cycle analysis of the fuel will be made for different ethanol sources. In chapter 15, the engine selection will be explained. After that, in chapter 16 the noise analysis of the chosen engine will be made. And finally, in chapter 17 some emergency solutions for the aircraft will be presented.

The next part, part IV, will give an overview of what is done in terms of structures and materials. First, in chapter 18 an aluminium analysis will be done. The properties of the materials will be analysed here. In chapter 19 the primary structure will be presented and in chapter 20 the primary structure will be analysed. In the next chapter, chapter 21, the secondary structures will be presented. In chapter 22 the structural joining will be analysed. In chapter 23 the wiring and electronics options will be listed and researched. And finally in chapter 24 the end-of-life plan will be presented.

Part V will deal with the operations and logistics of the aircraft. First, in chapter 25 the unit cost of the aircraft will be calculated and a dry lease price will be given. In chapter 26 the operational cost will be calculated and afterwards a wet lease price will be given. Finally, chapter 27 will deal with the supply chain management and the maintenance management.

Finally, part VI will conclude the report. In chapter 28 the verification and validation procedures will be listed and explained. In chapter 29 a comparison will be made between the Cessna Skycatcher and the InfiniCraft. In chapter 30 the impact of this project on the society will be given. In chapter 31 the future approach for this project will be explained. And finally, in chapter 32, the conclusion of this report will be given.

Chapter 2 | Cradle to Cradle® Philosophy

The Limits to Growth study [5] in 1972 addressed the question of how humanity would adapt to the physical limitations of planet Earth. The exponential growth of the population has a large impact on the availability of resources. In order to guarantee sufficient resources and acceptable living conditions for each individual, a change in our vision has to be made. A sustainable approach towards the environment is an important element in this vision. This approach includes also the design of Cradle to Cradle® products. The term Cradle to Cradle® (C2C) is used to describe a sustainability model which is imitative of natural processes, with the goal of enriching and benefiting the environment even as products are manufactured and used.

This model is based on the book *"Cradle to Cradle: Remaking the Way We Make Things"*, by Michael Braungart and William McDonough [3]. It calls for a radical change in industry by switching from a cradle to grave pattern to a Cradle to Cradle® pattern. This pattern is described in the following section. The last section of this chapter discusses how Cradle to Cradle® will be applied to the InfiniCraft.

2.1 Principles of Cradle to Cradle®

The purpose of Cradle to Cradle® is to eliminate the concept of waste entirely. A biological and technical cycle are used to eliminate this waste. This means that after the life of a product, all parts need be re-used without decreasing the quality of the material. These cycles are displayed in figure 2.1.

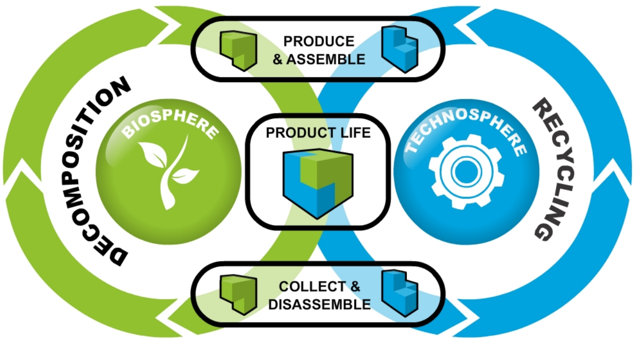

Figure 2.1: Cradle to Cradle® cycles [6]

In the biocycle, products support the biological metabolism after their use. In the technocyclce products containing non-degradable, scarce or toxic materials are safely disassembled and recycled [7].
The principles to succeed in Cradle to Cradle® are described below:

Waste equals food: Today, a lot of products end up as waste after they are used [8]. With resources becoming scarce, a lot can be gained by eliminating waste. The biocycle consists of all consumption products that can be broken down by nature. By making sure that each material that has been used in the design ends up in its respective cycle, waste can be eliminated.

Celebrate diversity: Nature is a complex system with variety and diversity. Cradle to Cradle® is not just about designing the right thing, it is also about choosing responsible supply chains and creating value through business collaboration. By implementing the way nature flourishes into product manufacturing, new company relations can be established creating new product solutions. These solutions can apply to both manufacturing and end-of-life of products.

Use current solar income: With energy resources depletion, it is crucial to change the ways of producing energy. Instead of burning fossil fuels, renewable energy sources should be sought. Solar energy driven power plants provide a solution to the resource problem by converting solar power, wind energy or biomass to energy. Designs should be able to function by using either of these resources.

2.2 Strategy Implementation in InfiniCraft

The challenge now is to design an airplane using the Cradle to Cradle® philosophy. Some specific points of interest are defined, which will be used to steer the design of the aircraft.

- Renewable energy: The energy used needs to be renewable energy. This can be achieved by using solar energy, wind energy or biomass energy. With "energy", all the energy is considered. This means it can be split up in three categories:
  - Manufacturing: During manufacturing a lot of energy is used. If a material is chosen, it is assumed the manufacturer uses renewable energy during the production process. This is set as a boundary because otherwise the focus of this project would not be the design of the aircraft.
  - Operations: All the energy used during the life of the aircraft will be renewable. This is achieved by choosing for biofuels or hydrogen. Both of these fuel sources are considered as renewable; biofuel (made from biomass or waste) because it absorbs CO_2 during its life and hydrogen because it only produces water when it is used in a fuel cell.
  - End-of-life: This is the same as the energy used during the manufacturing. All the companies that disassemble the airplane and/or recycle the components and materials need to use renewable energy.
- Maintenance: During the life of the airplane, components will need to be changed. Of course this needs to be done keeping the Cradle to Cradle® philosophy in mind. All the components that are taken off the airplane will be fully recycled and used again. The useful components will be sent back or used again in the maintenance centre.
- Waste management: During the manufacturing of the materials, some side products will be generated. A good way to reuse these side products needs to be present to close the cycles.
- CO_2 effectiveness: This point is treated in the same way as the green energy during operational life. Biofuel or hydrogen will make sure the aircraft will not emit more CO_2 than it can absorb during its life.
- End-of-life solutions: A very important step in the Cradle to Cradle® process is the end-of-life phase. To make sure the aircraft can be disassembled easily, this has to be taken into account during the design. With this, the aircraft will in fact be designed for disassembly. Some possible solutions are new joining methods, a modular design, etc. During the design of the fuselage and wings, this will be a major focus point. The aim is to have a 100% good product which leads to a fully recyclable aircraft, according to the principles of Cradle to Cradle®. The customer requirement states that the aircraft needs to be 90 % recyclable. The 90 % is defined as the ratio of the total recycled mass by the operative empty weight of the aircraft. This can be achieved in two different ways. Some of the parts will just be scrapped after their lifetime and the raw materials will be used again to make parts of the same quality. However, for some of the parts this will not be profitable. The parts that could be used again, will have a second life in another aircraft. But, in the end, all parts should be fully recyclable without a decrease in quality.

  But why not aiming for a 100 % fully recyclable design? The design of the InfiniCraft is made with the consideration that it should have no impact on future generations. It can be assumed that it is not possible to do this by 2025, but it should be feasible closely after 2025. Some parts of the aircraft can not be (fully) recycled (coating, electronics, rubber), but with novel techniques it is assumed this will improve towards and onwards from 2025.

Chapter 3 | Requirements

In this section the requirements defined for designing the Cradle to Cradle® aircraft are presented. Through the design phase, written down in this report, it will be determined whether the requirements are met or not.
Section 3.1 starts with enumerating the customer's requirements. Section 3.2 will elaborate further on the certification requirements.

3.1 Customer's Requirements

3.1.1 Design Requirements

- The unit cost shall not exceed $ 150 000 (USD)
- A total of 500 aircraft units shall be produced
- The aircraft shall be able to carry a total number of two passengers including the pilot
- The aircraft shall be on the market by 2025
- The aircraft shall have a minimum life span of 30 years
- The aircraft shall be designed for 20 000 flight hours
- The aircraft shall be designed for a total number of 12 000 flights

3.1.2 Mission Requirements

- The aircraft shall have a range of 1 000 km
- The aircraft shall have a cruising speed of 200 $^{km}/_{h}$
- The cruise altitude shall be 3 050 m
- The maximum take-off length shall be 500 m (on tarmac runways)

3.1.3 Cradle to Cradle® Requirements

- The aircraft shall be designed according to the Cradle to Cradle® principles [9]
  - At least 90% of the OEW shall be fully recyclable at the aircraft's end-of-life
  - Recycled materials shall be re-integrated through either the technical cycle or the biological cycle, according to the Cradle to Cradle® principles
  - A disposal plan for end-of-life shall be provided
- The aircraft shall be able to operate according to the Cradle to Cradle® principles
  - The aircraft shall have a carbon emission of no more than 50 $^{kg}/_{h}$
  - Current solar energy shall be used as an energy source for the aircraft

3.1.4 Additional Requirements

- The noise level shall not exceed 62 dB, measured according to the FAR Part 36 regulations
- An in-flight emergency solution shall be provided

3.2 Certification

The aircraft needs to be certified according to the rules of the FAA and EASA. There are several categories of aircraft which can be applied for certification. The ones that are suitable for the InfiniCraft are the CS-23 for Normal, Utility, Aerobatic and Commuter Aeroplanes (equivalent to FAR Part 23) [10] and the CS-VLA (Very Light Aircraft) [11]. The CS-23 certification allows for airplanes with a MTOW of up to 5 670 kg. CS-VLA on the other side, is more stringent and allows MTOW of up to 750 kg. Moreover, it only allows the InfiniCraft to fly during the day, under visual flight rules (VFR) conditions. It has been decided to certify the aircraft according to CS-23, since this will give the aircraft more flexibility in operation and as such will make the aircraft more competitive with comparable aircraft (like the Cessna Skycatcher).

Chapter 4 | Functional Flow Diagram

In this chapter the functional flow diagram will be presented and explained. This diagram will give an overview of all the basic functions of the aircraft that will be designed. The diagram is split up in two parts. First the overall functional flow (figure 4.1) is given. Secondly, a more detailed flow of the usage (figure 4.4) is presented.

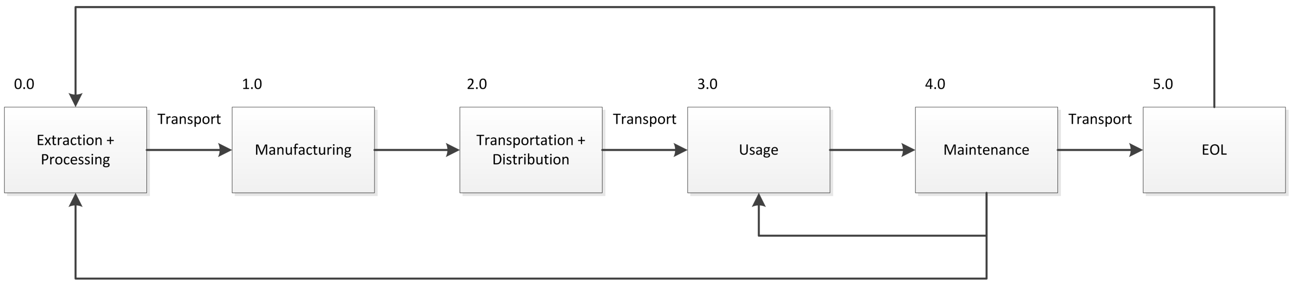

Figure 4.1: The functional flow diagram of the entire life of the Cradle to Cradle® aircraft

In figure 4.1, the functions of the life of the Cradle to Cradle® aircraft are listed. The first step in the process is the extraction and processing of the materials. These materials will go to the manufacturing process, where they will be used in parts for the Cradle to Cradle® aircraft. These parts will be assembled and a complete aircraft will be the result. This will be transported to the customer whereafter it will be used. During its life, the aircraft will require some maintenance. After this maintenance it can be used again and the broken parts will go back to the processing phase. At a point in time, maintenance will become too costly and the aircraft will go to the 'end-of-life' phase. Here it will be recycled to close the circle, the extracted materials will go to the process phase again and this will close the life cycle loop. This fits completely in the Cradle to Cradle® philosophy.

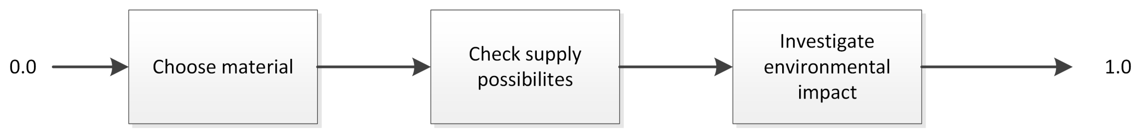

Figure 4.2: The functional flow of extraction & processing

Figure 4.3: The functional flow of manufacturing

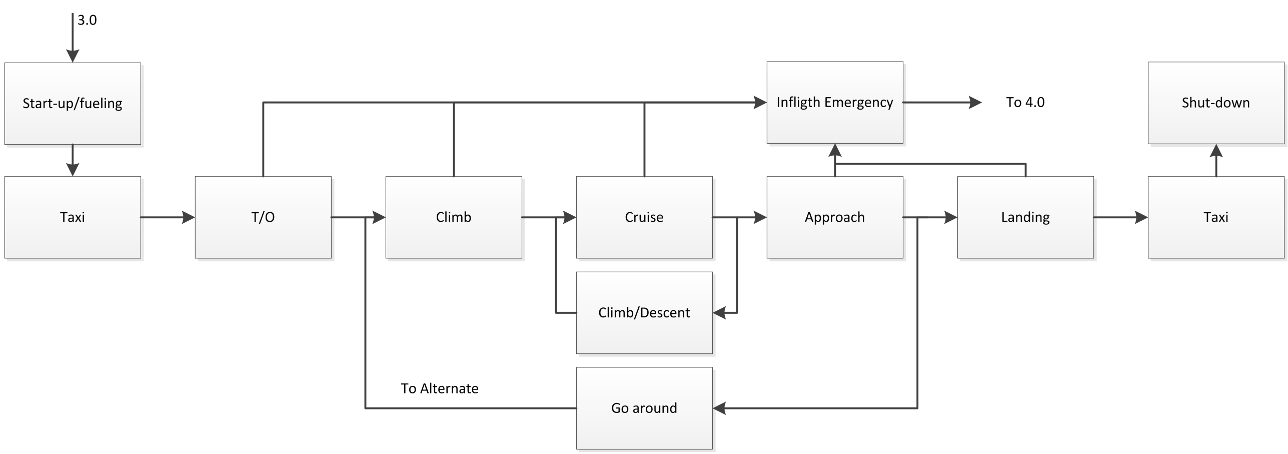

Figure 4.4: The functional flow of the usage of the aircraft

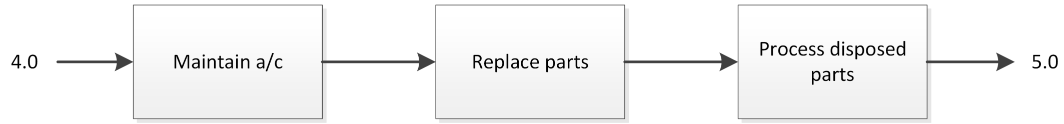

Figure 4.5: The functional flow of maintenance

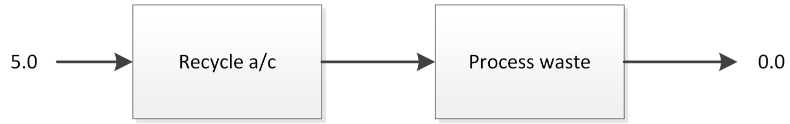

Figure 4.6: The functional flow of EOL

Figure 4.2 displays the functions during extraction and processing. A material has to be chosen out of the different possible suppliers. Also the environmental impact of the processing of the material has to be taken into account. Manufacturing is the next function, which can be found in figure 4.3. A modular design will be applied in which the different components of the system will be designed separately. The manufacturer will be allocated and a waste management policy will be defined. In figure 4.4 the functions during the usage of the aircraft are shown. In general, the functions will be: start-up, taxi, take-off, climb, cruise, approach, landing, taxi and shut-down. Sometimes, the flow will be a little different. Some examples: flying to an alternative destination, go around or an inflight emergency. The functions during the maintenance of the aircraft can be seen in figure 4.5. The disposed parts will be processed with respect to the Cradle to Cradle® philosophy. The last function is the EOL-procedure, dispayed in figure 4.6. The aircraft has to be recycled and the waste processed. After this phase, the complete cycle can be restarted, beginning with the extraction & processing phase.

Chapter 5 | Functional Breakdown Structure

The functional flow diagram explained in the previous chapter shows the functions the aircraft should perform in a chronological order. Next to this time-related categorisation, the functions could also be grouped in different categories in order to identify other, non time-related links between functions. This is done in the functional breakdown structure (FBS), which can be found below. With this categorization the design process can be done in a more structured way.

The grouping of the FBS is based on different phases of the aircraft's life cycle. For the sake of simplicity only one subdivision has been made in the FBS inserted in this report.

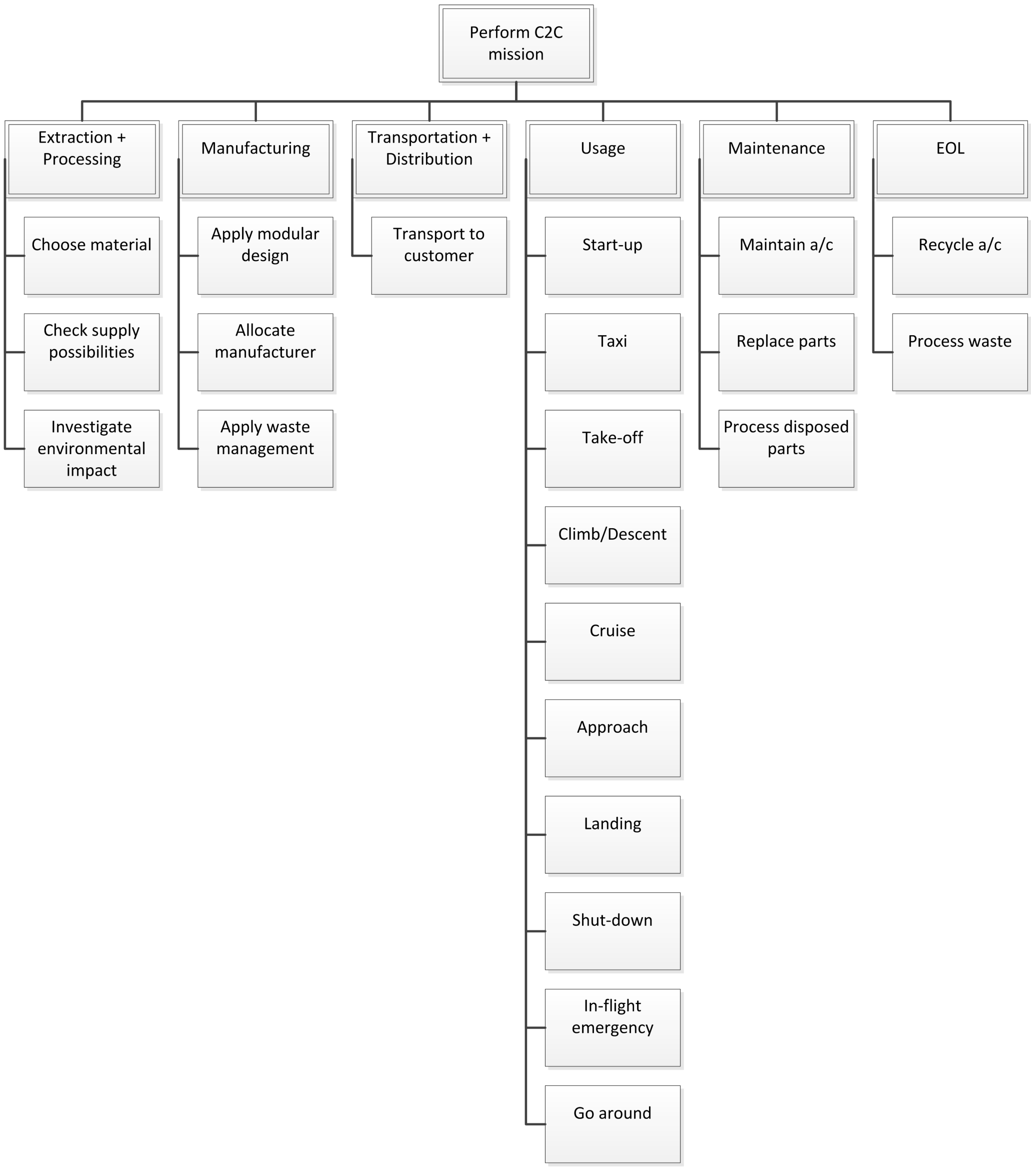

Figure 5.1: Functional breakdown structure of the Cradle to Cradle® aircraft

Chapter 6 | Interface Definition and N^2 Chart

Throughout the project definition phase, several subgroups have been working on possible concepts within their field of expertise. The final aircraft design will however be a multidisciplinary solution between each of those subgroups. In order to come up with such solution, interfaces have to be identified within those subgroups. These interfaces are worked out in a N^2 chart (see figure 6.1), which is treated in this chapter. A N^2 chart orders all of the functional units on the diagonal axis and identifies interactions between those units. First the functional units will be discussed, thereafter the interactions will be explained.

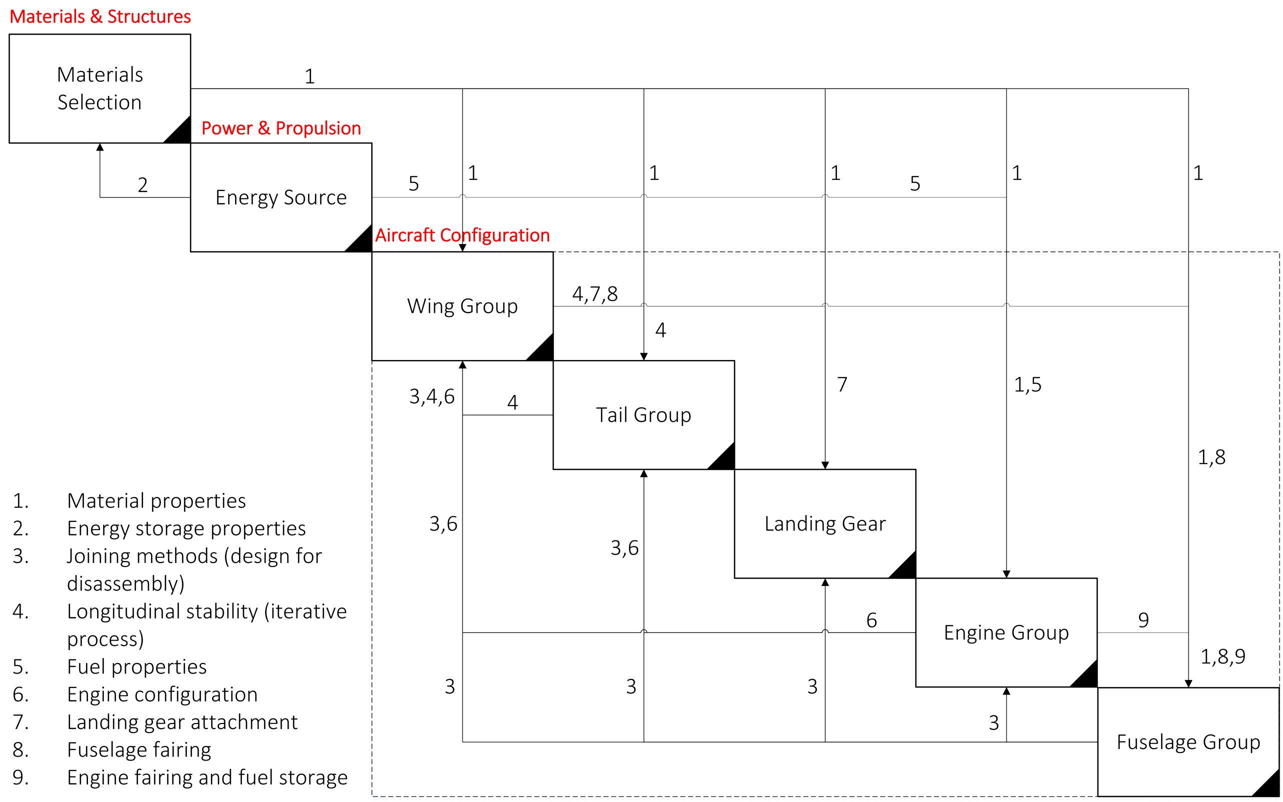

Figure 6.1: N^2 chart of the Cradle to Cradle® aircraft

6.1 Functional Units

The upper two functional units, material selection and energy source, are the two main contributors to Cradle to Cradle® aircraft design. Structural design has been integrated in each of the aircraft configuration groups. This approach makes it easy to identify interactions between the units. Also, separating the whole aircraft in those functional units allows for an easy integration of the modular design concept for the aircraft, which is another advantage of identifying those functional units this early in the design process. Five different configuration groups have been formed:

- The wing group: wing configuration and wing structure
- The tail group: tail configuration and tail structure
- The landing gear group: landing gear configuration
- The engine group: engine configuration and propulsion type
- The fuselage group: fuselage structure, interior, wiring and electronics

6.2 Interactions

In this section the interactions between functional units as well as the links will be explained. A reference to each one of the treated links will be put between brackets, where the numbers correspond to the numbers in figure 6.1.

The materials selection will provide material properties, which will be used for the design of each of the aircraft configuration groups (1). The only input that will influence the material selection is the energy source selection, as it will constrain the material type used for the storage of the energy (e.g. pressure vessel for hydrogen or conventional fuel tank for biofuels) (2). All other major interfaces will form links between the aircraft configuration groups.

The wing group will interact with the tail group for the stability analysis of the aircraft as both of their locations will influence the size, properties and location of each other (4). The wing group will also influence the attachment possibilities of the landing gear (7). Moreover, the wing geometry and location will influence the fuselage fairings, which are considered to be part of the fuselage group (8). Finally, the engine configuration will limit some of the wing configuration possibilities (6).

The engine configuration will influence the fuselage and tail group as an engine fairing will have to be implemented within the fuselage structure (9). The fuselage group will influence all of the other configuration groups (3). The reasoning for this is to consider the fuselage group as the central connection point of the aircraft design in the context of the 'design for disassembly' concept. Implementing joining methods inbetween the functional units that are easily disassembled, will improve the aircraft's recycling possibilities and will reduce the effort required for the end-of-life phase of the aircraft. The joining methods are thus looked at by the fuselage group, but implemented by the other structural groups.

Chapter 7 | Summary Trade-Offs

In this chapter the design trade-offs, as explained in detail in the mid-term report [12] are summarised. The first trade-off eliminates the "non-concepts" as well as the "not yet developed concepts". In the second trade-off the fuel selection is performed. The third trade-off is the most extensive one, in which four concepts are generated and compared to each other, finally the best concept is selected.

7.1 First Trade-Off

The first step in this trade-off is the identification of the non-concepts. Non-concepts are options "that are listed for the sake of completeness, but for which no implementation can be found" [13]. The elimination has been performed by investigating the design option trees from the baseline report [14].

The most important "non-concepts" are:

- Blended wing body (see figure 7.1)
- Retractable landing gear
- Flying wing
- Jet engine
- Solar panels
- Batteries

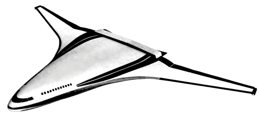

Figure 7.1: Example of a blended wing body: NASA N3-X [15]

The next step in the trade-off process is the identification of the "not yet developed concepts". Not yet developed concepts are options "that might be achievable, but are not worth pursuing now (e.g. new technologies for which you do not have resources to develop now or that are too difficult to analyse within your schedule)" [13]. The elimination has been performed by investigating the design option trees from the baseline report [14].

The most important "not yet developed concepts" are:

- Biocomposites as primary structure
- Prandtl wing as wing layout

7.2 Second Trade-Off

In this trade-off the fuel is selected. In the trade-off five criteria are compared for hydrogen and biofuel. The trade-off criteria are as follows: system weight, system price, fuel price, environmental impact and availability. For the two fuel types, scores are given for each criterion. The best option for that criterion is given a score of 100, the other is scaled according to its relative performance. The weights of each criterion are determined by a group survey.

The system weight includes the engine, fuel and fuel storage. In case of a hydrogen system also a fuel cell is included. The weight of the hydrogen system was found to be 453 kg, while the weight of the biofuel system is 342 kg. The ratio of these weights equals 0.75, therefore biofuel scores 100 and hydrogen scores 75.

The system price is determined by the engine, fuel tank and other equipment such as fuel pumps (for hydrogen this includes the balance of plant). The cost for a hydrogen system is $ 49 500, while the cost for a biofuel system is $ 37 090. The ratio of these prices equals 0.75, therefore biofuel scores 100 and hydrogen scores 75.

The price for a fuel tank is determined by comparing fuel cost and the energy required from the fuel (needed volume). In the case of hydrogen this leads to a price for a full tank (sized for required range) of $ 120. For biofuel a price of $ 173 is found. The ratio of these prices equals 0.69, therefore biofuel scores 69 and hydrogen scores 100.

The environmental impact is compared using five parameters; land use, competitiveness with the availability of food, competitiveness with the availability of water, CO_2 & CH_4 emission and the production of waste products. In the end the score ratio of biofuel and hydrogen equals 0.72, therefore biofuel scores 72 and hydrogen scores 100.

The availability is compared by looking at the fit with current infrastructure, barriers of change in infrastructure and by looking at third party demand of resource. After comparing the factors for both fuel types, a ratio of 0.69

was found between hydrogen and biofuel. For this reason, biofuel gets a score of 100, while hydrogen receives a score of 69.

Table 7.1: Fuel selection trade-off matrix

	Weight Factor	**Hydrogen**	**Biofuel**
System Price	0.64	75	100
Fuel Price	0.67	100	69
System Weight	0.69	75	100
Environmental Impact	0.93	100	72
Availability	0.81	69	100
Score		315	**327**

The results are summarised in a trade-off matrix. The matrix is displayed in table 7.1. As can be seen, biofuel has the highest score. The difference in final score is only 3.8% which is not really significant, therefore it was decided to validate the choice for biofuel with the group philosophy. A test was established to monitor the individual design preferences. The results of this test were in line with the score of the trade-off matrix and hence it provides enough support to safely choose for biofuel.

7.3 Third Trade-Off

After the first and second trade-off four concepts were created. In this trade-off one of those concepts is chosen. First the four concepts are introduced, than the trade-off criteria are described and finally the trade-off weights and results are shown. Like in the second trade-off the weights are obtained using a group survey.

7.3.1 Concepts

The concepts that were created for the third trade-off are shown in figure 7.2, 7.3, 7.4 and 7.5. The sketch of concept I, figure 7.2, is identical to the sketch of concept II, figure 7.3 but the materials used for the primary and secondary structure are different.

Figure 7.2: Sketch of concept I

Figure 7.3: Sketch of concept II

Figure 7.4: Sketch of concept III

Figure 7.5: Sketch of concept IV

The properties of the concepts are summarised in table 7.2.

Table 7.2: Properties of the four concepts

Concept	Primary Structure	Secondary Structure	Lay-out		
			Wing	**Tail**	**Propeller**
Concept I	Aluminium	Thermoplastic Composites	High	Low	Tractor
Concept II	Wing: Aluminium Fuselage: Thermoplastic Composites	Thermoplastic Composites	Low	T-tail	Tractor
Concept III	Aluminium	Aluminium	Low	T-tail	Push
Concept IV	Thermoplastic Composites	Thermoplastic Composites	High	Low	Tractor

7.3.2 Trade-Off

In the trade-off seven criteria are used: weight, unit cost, operational cost, environmental impact, recyclability, availability by 2025 and flying characteristics. The concepts are then given scores. Part of the scores are easily scaled using the absolute weight or cost. Some of the criteria are given scores based on a group discussion. The detailed results are discussed in chapter 6 of the mid-term report [12]. The results are summarised in table 7.3.

Table 7.3: Trade-off matrix for the third trade-off

Criterion	Weight factor	Concept I	Concept II	Concept III	Concept IV
Weight	0.70	93	79	88	100
Unit cost	0.63	100	60	97	55
Operational cost	0.84	100	80	95	85
Environmental impact	1.00	90	85	95	100
Recyclability/EOL	0.92	100	90	90	75
Availability in 2025	0.69	100	85	90	75
Flying characteristics	0.57	90	70	80	100
Total score		514	422	488	454

From the results it can be seen that concept I has the highest score. This concept scores 100 in four out of seven concepts and therefore it is the best concept regarding those criteria. From this point on concept I will be selected for further analysis. As a reference aircraft, the Cessna Skycatcher is used, which has a very similar configuration [16].

PART II

AIRCRAFT SIZING

“Our concept of eco-effectiveness means working on the right things - on the right products and services and systems - instead of making the wrong things less bad.”

William McDonough,

Co-author of the book *Cradle to Cradle: Remaking the Way We Make Things*

Chapter 8 | Initial Sizing

With the use of a power and wing loading diagram, an initial sizing of the aircraft can be done. With this method, the aircraft is sized for stall speed, take-off and landing length, climb rate and climb gradient. Each of these flight actions has its own requirements, either from the customer's requirements or certification requirements. With these requirements (for example a climb rate of 5 m/s), the required power loadings (W/P) and wing loadings (W/S) can be computed. The equations used for the generation of these diagrams can be found in the slides of AE1201: Aerospace Design and Systems Engineering Elements I [17].

The calculations to compute the diagram require several inputs. The input parameters are shown in table 8.1. The last column of the table indicates the source of the parameter value. The air density is dependent on height and temperature. Since the air density is used for take-off configuration, landing configuration and climb conditions, sea level values are used. To account for warm days, the air density is picked at a temperature of 35°C.

Table 8.1: Input parameters initial sizing

Parameter	Value	Reference
Air density (ρ_0)	1.225 [kg/m^3]	International Standard Atmosphere (sea level)
Air density (ρ)	1.146 [kg/m^3]	International Standard Atmosphere (35°C)
Stall speed (V_{stall})	31.4 [m/s]	CS-23 [10]
Stall speed @ landing (V_{stall})	26.0 [m/s]	-
Take-off speed (V_{TO})	34.5 [m/s]	-
Take-off parameter (TOP)	48.552 [-]	Raymer Method [18]
Density ratio	0.935 [-]	-
Landing distance	400 [m]	Assumption
Ratio take-off and landing weight (f)	0.997 [-]	Roskam [19]
S_{wet}/S	3.8 [-]	Reference aircraft
The friction and pressure drag coefficient (C_{D0})	0.0335 [-]	Roskam [19]
Oswald factor (e)	0.7 [-]	Reference aircraft
Propeller efficiency (η_p)	0.8 [-]	Assumption
Climb rate (cr)	5 [m/s]	Reference aircraft
Climb gradient (c/V)	0.083 [-]	CS-23.65 [10]
Obstacle height	10.7 [m]	CS-25.113 [10]
Conversion factor	0.2856 [-]	Raymer Method [18]

The required power and wing loadings can be plotted in a W/S-W/P-diagram, see figure 8.1. Different lines are plotted, each for a different requirement and design parameter (lift coefficient, aspect ratio etc.). In the end, the power and wing loading should be set as high as possible. This means that the design point should be chosen in the upper-right corner of the feasible region. However, when a line is crossed, the design gets more complex, for example a higher lift coefficient is required (thus resulting in more complex flap systems). Summarised: the goal is to get to the upper-right corner, without crossing too many lines (and making the design too complicated).

The final design point that was chosen is bounded by a landing lift coefficient ($C_{L,landing}$) of 1.9, a take-off lift coefficient ($C_{L,TO}$) of 1.5 and a clean configuration lift coefficient ($C_{L,clean}$) of 1.1. The last boundary to account for is an aspect ratio of 7. As can be seen from the diagram, this design point is very reasonable compared to reference aircraft.

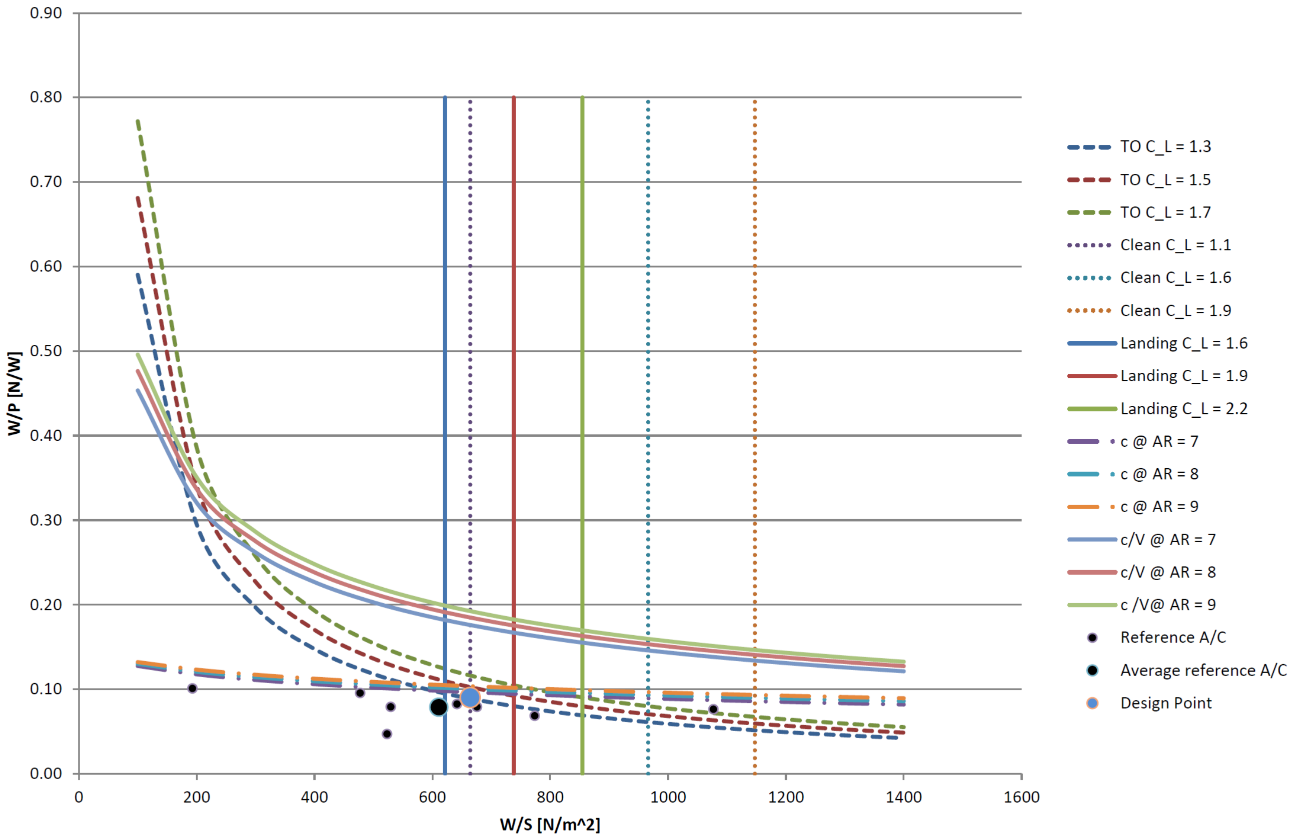

Figure 8.1: Wing and power loading diagram

The difference between clean and landing configuration is less than 0.9. Plain flaps are generally able to produce a ΔC_L of 0.9 and are therefore sufficient. With the chosen design point, the wing loading (W/S) is set to 664 $^N/_{m^2}$ and the weight-to-power ratio is set to 0.09 $^N/_W$.

The value for the wing loading leads to a surface area of 10.4 m^2, a take-off power of 103 hp and a wing span of 8.5 m. Since the configuration of the design is comparable with a Cessna Skycatcher, the same airfoil is chosen. The airfoil that will be used is a NACA 2412 [20]. The results are summarised in table 8.2.

Table 8.2: Summary output parameters initial sizing

Parameter	**Value**
Lift coefficient in landing configuration ($C_{L,landing}$)	1.9 [-]
Lift coefficient at take-off ($C_{L,TO}$)	1.5 [-]
Lift coefficient in clean configuration ($C_{L,clean}$)	1.1 [-]
Wing surface area (S)	10.4 [m^2]
Aspect ratio (AR)	7 [-]
Wing span (b)	8.5 [m]
Take-off power (P_{TO})	103 [hp]
Wing loading (W/S)	664 [$^N/_{m^2}$]
Weight-to-power ratio (W/P)	0.09 [$^N/_W$]
Flaps	Plain flaps: ΔC_L up to 0.9
Airfoil	NACA 2412

Chapter 9 | Weight Estimation

With the wing and power sizing now performed, a weight estimation can be performed. In this chapter, the results of a class I and II weight estimation are described. First a class I weight estimation is performed. The results of this estimation is used as an input to the class II weight estimation.

9.1 Class I Weight Estimation

Before a class II weight estimation can be performed, an initial weight estimate needs to be made. This can be done via a class I weight estimation. This method uses statistics based fuel fractions. The aircraft's weight is split up in three parts: the OEW, the payload weight and the fuel weight. The OEW can be found by looking at comparable reference aircraft. The reference aircraft that were used can be found in the baseline report [14]. Making use of a linear regression line, a relation can be established between MTOW and OEW. This is shown in figure 9.1.

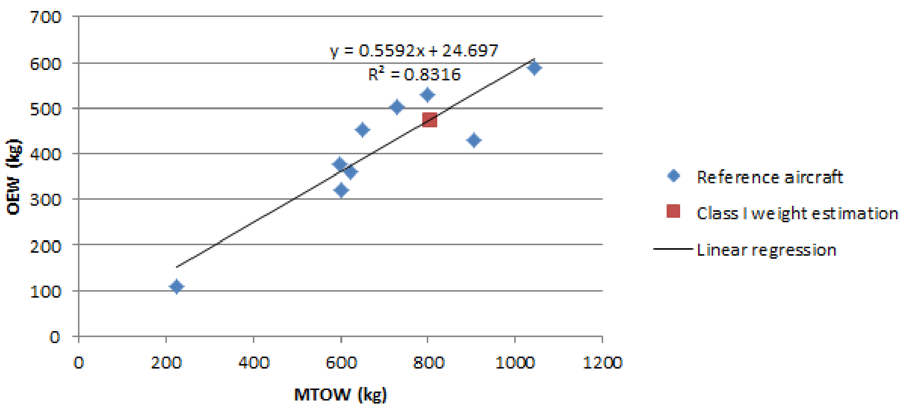

Figure 9.1: Linear regression of MTOW as a function of OEW for the class I weight estimation.

Next the payload weight needs to be determined. The payload weight is based on transporting two passengers plus their baggage. Based on standard values from Roskam [19] the payload weight has a value of 181.2 kg (2 passengers of 77 kg and 2 pieces of 27.2 kg baggage).
Finally, the fuel weight can be estimated using fuel fractions. The fuel fractions are based on values from Roskam [19]. With the Breguet range equation [17] the fuel fraction for the cruise phase is calculated. Here a range of 1 000 km, specific fuel consumption of 1.01e-7 kg/J, a propeller efficiency of 0.8 and a lift over drag ratio of 9 is assumed.
With estimations for each of the three weight components, a weight estimation can be made. The results are shown in table 9.1. In figure 9.1 it can be seen that the estimation perfectly fits the linear regression curve, so the estimate seems reasonable.

Table 9.1: Results of the Class I weight estimation

Parameter	**Weight** $[kg]$
Empty Weight	520
Payload Weight	181
Fuel Weight	141
Take-off Weight	885

9.2 Class II Weight Estimation

After the Class I weight estimation, a Class II estimation is performed. This is done through a component weight estimation. Again the method of Roskam [21] is used. This method estimates the weight of each major component of the aircraft. The equations are based on data from reference aircraft.

It is important to note that a loop exists between the chosen wing and power loading of chapter 8 and the class II weight estimation. An example of this is that a higher weight requires a larger wing surface, which leads to again a higher weight. The weight estimation is therefore iterated several times, until the differences between the weight estimations becomes sufficiently small (less than 1%).

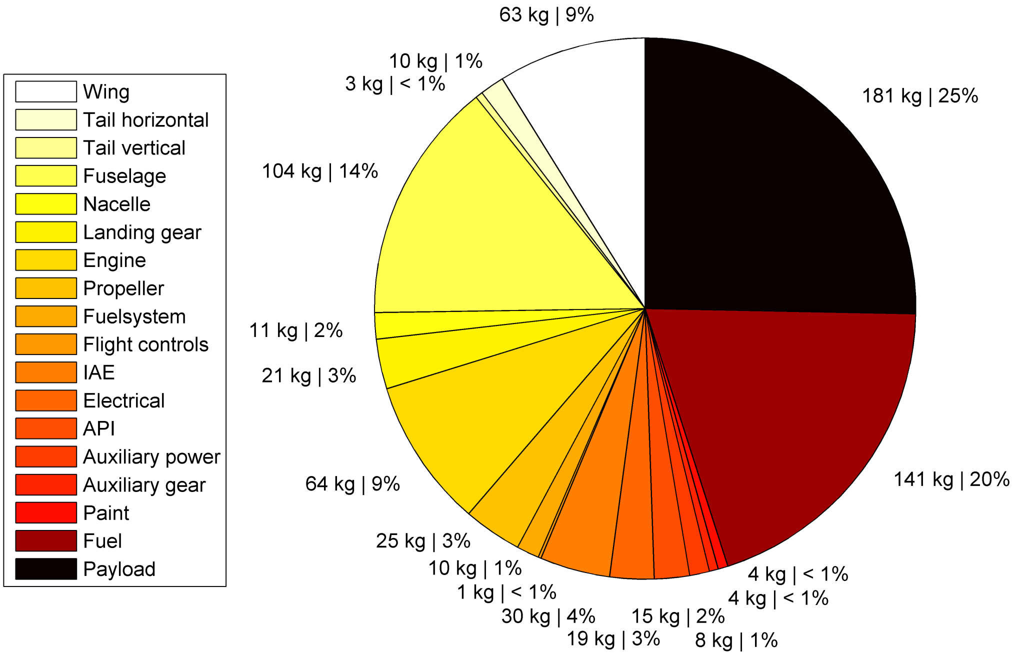

Figure 9.2: Baseline class II weight estimation used for structural sizing, fuel tank sizing and other analyses

Besides the loop between the wing and power loading, there are other loops between for example the fuel weight, structural sizing and the weight estimation. These are not very easily iterated, because they require more computational work (e.g. the structural sizing is a time-intensive process and not simply a code to run). Because of these loops, initially a baseline weight estimation is made, which is shown in figure 9.2. An OEW of 393 kg and a MTOW of 716 kg is obtained.
This estimation serves as a basis for the fuel tank sizing, structural sizing and other design choices in the chapters to come. In the end, when all analyses have been performed, a final weight estimation is performed. This is included in appendix F.

Chapter 10 | Stability & Control

As part of the sizing of the aircraft, a stability and control analysis needs be performed. With this analysis, more information on the aircraft's geometry can be obtained, specifically the horizontal tail size. The analysis consists of several steps, that will each be explained in this chapter.

10.1 Centre of Gravity of the Empty Aircraft

The stability and control analysis starts out with the determination of the centre of gravity of the empty aircraft. The weight of each separate component can be obtained from the class II weight estimation. The location of each component is measured from the nose of the aircraft, such that no negative coordinates need to be used. The components' locations are first estimated based on the reference aircraft Cirrus SR20 and the Cessna Skycatcher. During the course of the project, more information on the locations will become available. As such the following calculation should be continuously updated. The data that is used for the calculation is shown in table 10.1.

Table 10.1: Assumed mass and location of each major aircraft component

Component	**Mass** $[kg]$	**Location of c.g. from nose** $[m]$
Wing	63	2.48
Horizontal tail	10	5.96
Vertical tail	3	6.33
Fuselage	104	3.23
Nose landing gear	4	0.87
Main landing gear	18	2.73
Engine	63	0.99
Propeller	25	0.32
Fuel system	10	2.48
Flight controls	1	3.97
Instrumentation, avionics and electronics	30	1.74
Electrical	19	2.48
Airconditioning, anti- and de-icing system	15	3.72
Auxiliary power	8	3.72
Auxiliary gear	4	2.48
Paint	4	2.48
Total (OEW)	393	2.39

As can be seen from table 10.1, the centre of gravity of the empty aircraft is located at 2.39 m, measured from the nose.

10.2 Loading of the Aircraft

As a next step, loading diagrams need to be generated, to analyse how the centre of gravity will shift during loading of the aircraft. This is done for three different wing locations, such that the effect of wing location on the stability of the aircraft can be investigated. In table 10.2 the assumed locations of the payload and fuel are shown. In figure 10.1 the loading diagrams are shown.

Table 10.2: Assumed mass and location of the payload and fuel

Component	**Mass** $[kg]$	**Location of c.g. from nose** $[m]$
Passenger 1	77	2.35
Passenger 2	77	2.35
Baggage	27.2	2.98
Fuel	141	2.98
Total	322	

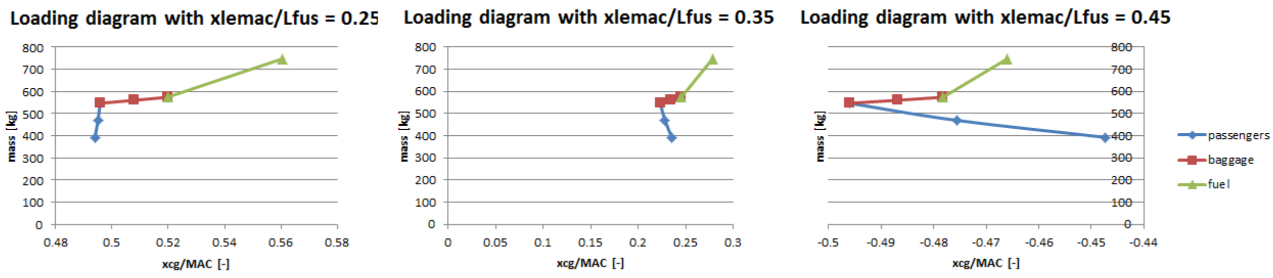

Figure 10.1: Loading diagrams for three different wing locations (xlemac = location of leading edge of the mean aerodynamic chord, lfus = length of the fuselage)

10.3 Centre of Gravity Range Plot

For each of the three cases in section 10.2, the minimum and maximum location can be read from the plots. These indicate the range of the centre of gravity that should be accounted for in the design of the aircraft. The centre of gravity range can be plotted as a function of the wing location. This is shown in figure 10.2 and is called a centre of gravity range plot.

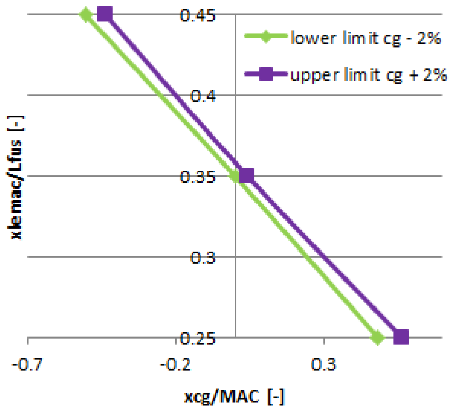

Figure 10.2: Center of gravity range plot

10.4 Stability and Controllability Curves

In order to size the aircraft the limits for stability and controllability should be investigated. When the centre of gravity lays to much aft, the aircraft becomes unstable. When the centre of gravity lays to much forward, the aircraft becomes uncontrollable (i.e. too stable). First the limit for stability can be calculated. This is done with equation 10.1 [22].

$$\bar{x}_{cg} = \bar{x}_{ac} + \frac{C_{L_{\alpha_h}}}{C_{L_\alpha}}\left(1 - \frac{d\epsilon}{d\alpha}\right)\frac{S_h l_h}{S\bar{c}}\left(\frac{V_h}{V}\right)^2 - 0.05 \tag{10.1}$$

Many assumptions are required on the aerodynamic centre location, the lift coefficients of the wing and tail etc. The assumptions are based on the initial sizing (e.g. the NACA2412 airfoil and its coefficients), geometry of the Cessna Skycatcher and statistical values from the lecture slides of Systems Engineering & Aerospace Design [22]. In table 10.3 the parameters and their assumptions are shown.

Table 10.3: Parameters for the calculation of centre of gravity limits for stability and controllability

Parameter	Value	Source
x_{ac}/MAC	1.94	Geometry
C_{L_h}	-0.1	Estimation
$C_{L_{\alpha_h}}$	5.73	NACA0012
$C_{L_{a-h}}$	0.8	Estimation
C_{L_α}	6.19	NACA2412
$c_{m_{ac}}$	-0.07	NACA2412
$\frac{d\epsilon}{d\alpha}$	0.052	Estimation
l_h	3.72	Geometry
$\bar{c}$	1.24	Initial sizing (chapter 8)
$(V_h/V)^2$	0.85	Statistical data [17]

It has been chosen, based on reference data, that a stability margin of $0.05 \cdot MAC$ will be used. This means that the most aft centre of gravity location should always lay in front of the stability limit by a distance of $0.05 \cdot MAC$.

The center of gravity should however not lay too much to the front, to assure that the aircraft can still be controlled. This forward limit for controllability can be calculated by using the parameters from table 10.3 and equation 10.2.

$$\bar{x}_{cg} = \bar{x}_{ac} - \frac{C_{m_{ac}}}{C_{L_{A-h}}} + \frac{C_{L_h}}{C_{L_{A-h}}} \frac{S_h l_h}{S\bar{c}} \left(\frac{V_h}{V}\right)^2 \quad (10.2)$$

The limit for stability can be combined with the limit for controllability. With this a so-called scissor-plot is generated. This is shown in figure 10.3.

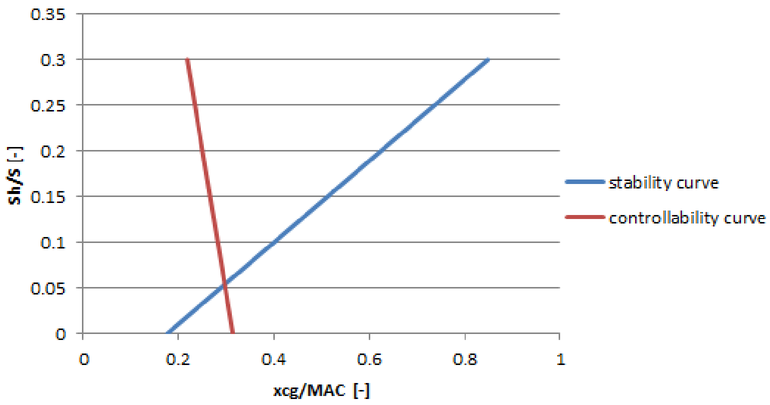

Figure 10.3: Scissor plot to determine the minimum and maximum allowable limits for the centre of gravity

10.5 Determination of Optimal Tail Size

As a final step in the stability and control analysis, the centre of gravity range plot can be overlayed with the scissor plot. This should be done in such a way that the actual centre of gravity range (centre of gravity range plot) coincides with the allowable centre of gravity range (scissor plot). Then the optimal tail size is found. This is shown in figure 10.4.

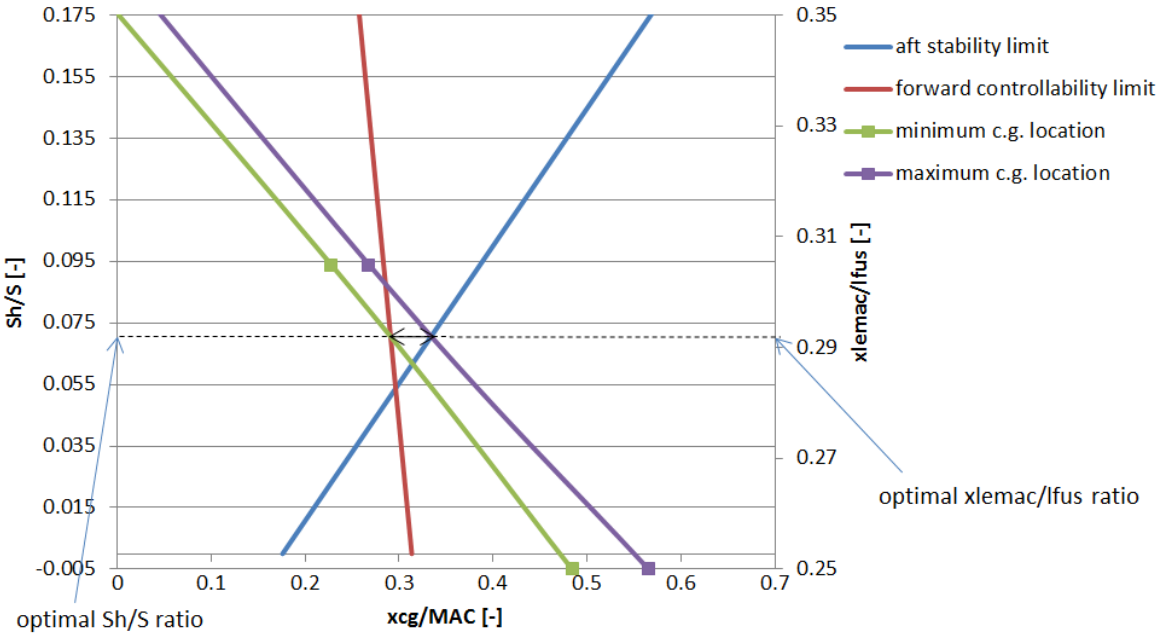

Figure 10.4: Combination of the centre of gravity range plot and scissor plot

From the figure it can be seen that the optimum between actual centre of gravity range and allowable centre of gravity range is reached with a tail over wing surface ratio ($^{S_h}/_{S}$) of 0.07 and wing location ($^{x_{lemac}}/_{l_{fus}}$) of 0.292. This yields a horizontal tail surface of 0.73 m^2 and a wing leading edge location of 2.03 m from the nose of the aircraft. With this the stability and control analysis has been finished.

Chapter 11 | Exterior Dimensions

As a conclusion to the initial sizing, weight estimation and control & stability analysis of the previous chapters, an overview of the aircraft's dimensions is given, see figure 11.1. From the initial sizing the wing parameters are known. From the stability and control analysis, the tail surface is known. Any other dimensions are based on reference aircraft. The InfiniCraft has a conventional configuration and as such it is assumed that dimensions like fuselage length, vertical tail surface etc. will not differ significantly from existing aircraft. The dimensions in figure 11.1 will be used throughout the remainder of the report.

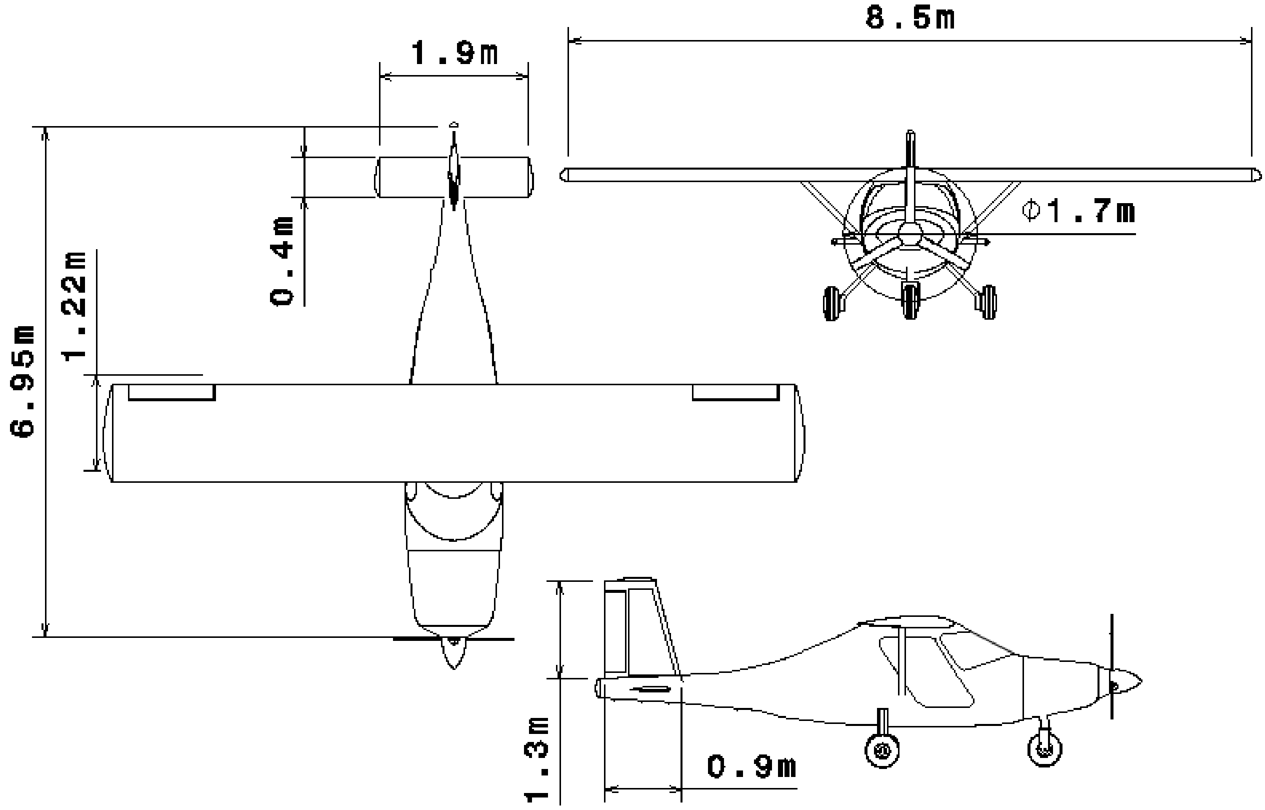

Figure 11.1: Top, side and front view of the InfiniCraft, with dimensions

Chapter 12 | Control System Design

The aircraft flight control system includes the control surfaces, the connecting linkages and the actual controls in the cockpit. From the 'concept I column' in table 7.2, it can be seen that the secondary structures of the InfiniCraft, and thus also the control surfaces, will be made from short-fibre reinforced thermoplastic composites.

For the connecting linkage between the cockpit and the control surfaces, three options exist: mechanically, hydro-mechanically and fly-by-wire [23].

- Mechanical control system let the pilot control the aircraft through cables or rods that are directly connected to the control surfaces. This method has been used on the most early aircraft and are nowadays often used for small aircraft. The pilot is in direct contact with the aerodynamic forces and as such these should not be too large to control the aircraft.
- When the aerodynamic forces become too large, a hydro-mechanical control system can be used. With this system, the control surfaces are controlled via a hydraulic system. This system is still however actuated through a cable system connecting the cockpit to the hydraulic pumps. A recent development is the introduction of the fly-by-wire system. In this system the control cables are replaced by an electronic control system. In this way, the pilots inputs can be interpreted and translated to control surface movement by a computer. It is mainly used on large jet aircraft; there are no fly-by-wire aircraft in general aviation yet, but the technology is of interest to the industry.
- Fly-by-wire has many advantages for the aircraft: it can provide a more stable flight, empennage can be downscaled (since the computer can correct for the instability), the flight envelope can be electronically bounded to avoid dangerous flight manoeuvres. There are however also some major drawbacks: the costs are high, the complexity is high, and for the Cradle to Cradle® aircraft it means extra electronics that are hard to recycle. Finally, there is the fact that the aircraft should be a trainer aircraft, in which student pilots should learn how to fly standard general aviation aircraft without fly-by-wire.

It was concluded that the advantages do not compensate for the disadvantages. As such the fly-by-wire option is discarded. Finally, since the aircraft is relatively small and as such will experience small aerodynamic forces, mechanical control system will be sufficient. This conclusion is based on reference aircraft; they use mechanical systems as well. This will save the costs and complexity of a hydraulic system, improving the EOL possibilities of the aircraft.

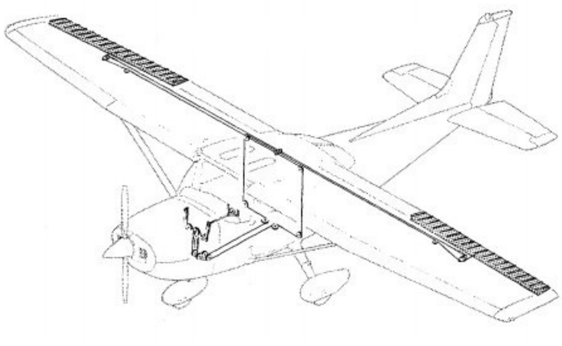

Figure 12.1: Aileron control system [24]

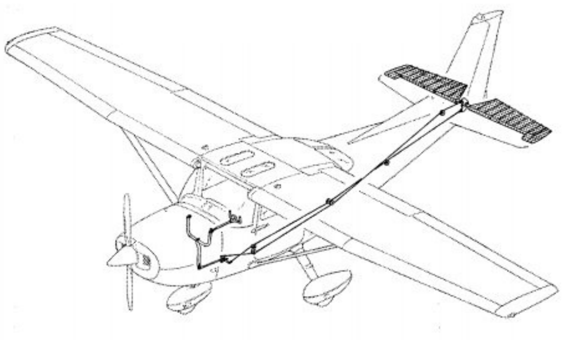

Figure 12.2: Elevator control system [24]

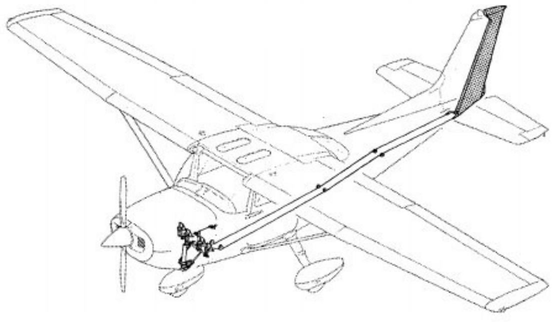

Figure 12.3: Rudder control system [24]

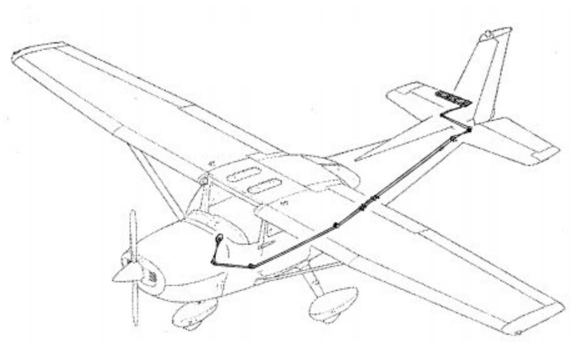

Figure 12.4: Elevator trim system [24]

For the connecting links between cockpit and control surfaces, two options exist: cables or rods. Both have advantages and disadvantages.

Cables

An advantages of a cable control system is the easy disassembly. When both ends of the cable are loose, the cable can just be pulled out of the airframe.
A disadvantage is that the cable may suffer from slack (because of temperature differences and other factors). This can be inconvenient when controlling the aircraft.

Rods

Advantages of rods are:

- There is direct feedback from the control forces.
- Rods can be made from either steel and aluminium. When made from aluminium, the rods and the airframe are of the same material, which facilitates the recycling.

A disadvantage is:

- Rods require a more complex structure compared to cables, especially with a high wing configuration, since many changes in direction are required when traveling from the cockpit to the control surfaces.

It should be investigated whether rods or cables will induce extra weight. This can be done in the detailed design of the control system, something that will not be done in this report, since it does not contribute to the Cradle to Cradle®-focus of this project. For further analysis it will be assumed that cables are used for the flight control system. The easy disassembly of the cable system is the main factor for this decision. The cables can be made from steel, which is already present in the landing gear. In this way, the steel from the control system can be recycled together with the steel from the landing gear.

PART III

POWER & PROPULSION

"I can leave here and go north to Canada or south to Mexico. If I find myself going 100 miles per hour towards Canada, but I'm supposed to be going to Mexico, it's not going to help me to slow down to 20 miles per hour."

William McDonough,

Co-author of the book *Cradle to Cradle: Remaking the Way We Make Things*

Chapter 13 | Fuel

In this chapter ethanol will be analysed as it will be the energy source of the InfiniCraft's propulsion system. In the first section a summary is provided on the trade-off that was carried out prior to the fuel selection. In the second section the properties of ethanol are discussed. Next, in the third section, the weight-range diagram is provided. Finally, the production possibilities of ethanol are investigated.

13.1 Biofuel Selection

After the second trade-off (of which a recap can be found in chapter 7) the type of biofuel needs to be defined. The most important types of biofuel are: bio-avgas, bio diesel and ethanol. These fuels need to be compared, before a choice can be made. The trade-off can be found in table 13.1. Availability and energy density are preferably as high as possible, while the price needs to be as low as possible. For a more detailed overview of this trade-off, the midterm report can be consulted [12].

Table 13.1: Trade-off of the fuels

Criterion	Bio diesel	Ethanol	Bio-avgas
Availability	Medium	High	Low
Price	Medium	Low	High
Energy Density	High	Low	High

After looking at this table, a fuel can be selected. At first glance, bio-avgas is not suitable: the availability is too low and the price too high. The remaining fuels are biodiesel and ethanol. At first sight, bio diesel looks better because of the higher energy density. In the Cradle to Cradle® philosophy ethanol would be better because it can be made from waste and non-edible plants. The price and the availability of ethanol are also better. These facts lead to the final choice for ethanol.

13.2 Fuel Properties

Ethanol is a type of fuel which is produced from biomass or biological waste. An engine can run on 100% bio-ethanol, E100 for short, or it can be mixed with avgas. For the Cradle to Cradle® aircraft, E100 will be used as primary fuel source. Its properties are discussed in table 13.2. At airports where E100 is not available, E85 (85 % ethanol mixed with 15 % avgas) might also be used.

Table 13.2: Ethanol properties

Criterion	Biodiesel
Density	721 kg/m^3 [25]
Heating value	21.63 MJ/L
Energy density	30 MJ/kg [26]
Price per liter	1.00 $\$/L$
Price per MJ	0.046 $\$/MJ$

The feasibility of using E100 to propel an aircraft can be proven by looking at the Embrear Emb 202A Ipanema aircraft (see figure 13.1), which runs on ethanol E100. This agricultural aircraft, which was certified in October 2004, is widely used in Brazil for crop dusting. This aircraft has some advantages compared to its predecessor, the Embraer EMB 202 Ipanema, which was certified in December 1971 and runs on conventional fuel [27] [28]. These advantages are:

- The engine runs cooler, which reduces wear and allows longer intervals between engine overhauls
- More power is produced
- Operating costs are significantly reduced

Figure 13.1: Embrear Emb 202A Ipanema [29]

13.3 Production Possibilities

One of the advantages of ethanol is that it can be made from different sources. This is however also the biggest pitfall, because the production needs to fit within the Cradle to Cradle® philosophy. Not only the CO_2 emissions need to be taken into account but also the ethical questions need to be considered. A distinction is made between first generation biofuels and second generation biofuels

13.3.1 First generation biofuels

First generation biofuels are made from food competing crops. This means the plants can be used as food if they are not used for making biofuels. A good example here is corn, which is commonly used in the USA as a source for ethanol. Ethanol is mixed with normal fuel and used for cars. This fits within the Cradle to Cradle® principle, because the corn absorbs CO_2 during the life of the crop. This makes the fuel (almost) CO_2 neutral. But now the question rises: "Should we use food to make a fuel that is used for luxury purposes?" There is a shortage of food in the world, so it may not be the best idea to use food as fuel. [30]

13.3.2 Second generation biofuels

Recently, some second generation biofuels are invented. These fuels are made from waste or plants that are not competing with food. Some examples are: sugarcane (if it is not especially grown to make ethanol!), waste and switch grass. These plants can grow on places were food crops can not grow. This means they are not competing with food crops. These biofuels are not necessarily better regarding CO_2 emission, but they are definitely better for a sustainable future of our planet. This is why second generation biofuels are preferred for the InfiniCraft [30].

13.4 Weight-Range Diagram

A weight-range diagram visualises the weights of the payload and fuel as a function of the range.

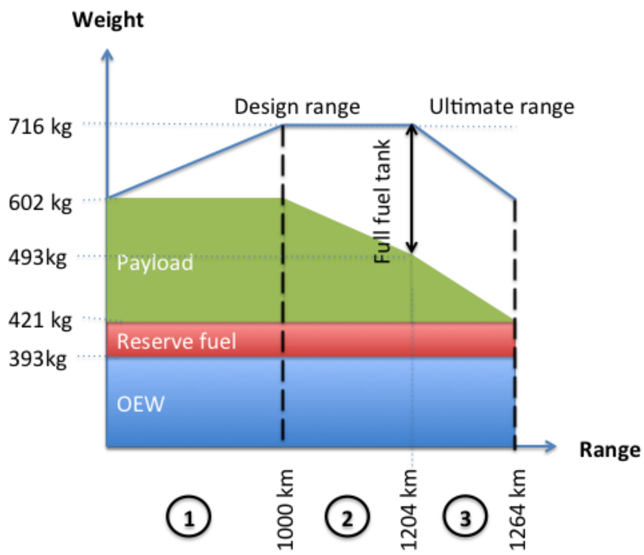

Figure 13.2: Weight-range diagram of the InfiniCraft

As shown in figure 13.2 both OEW and reserve fuel weight are independent of the range flown. The two components that are changing as a function of the range are the payload and the mission fuel. In order to explain their behaviour as a function of the range, the range must be divided into tree intervals:

- Region 1: range varies from 0 to 1 000 km, the design range. This is a linear relation between fuel weight and range.
- Region 2: range varies form 1 000 to 1 204 km, here the payload is reduced while the fuel weight is increased.
- Region 3: range varies from 1 204 to 1 264 km, the ultimate range of the InfiniCraft, here the payload is further decreased while the fuel tanks are already full. However, this range can never be achieved as there is always the need of the pilot, which is also considered as payload in general aviation.

In order to visualise the different ranges of the InfiniCraft figure 13.3 is added. In figure 13.3 it is assumed that the aircraft takes-off at the airport of Rotterdam. The range changes depending on the amount of fuel and payload on board of the aircraft.

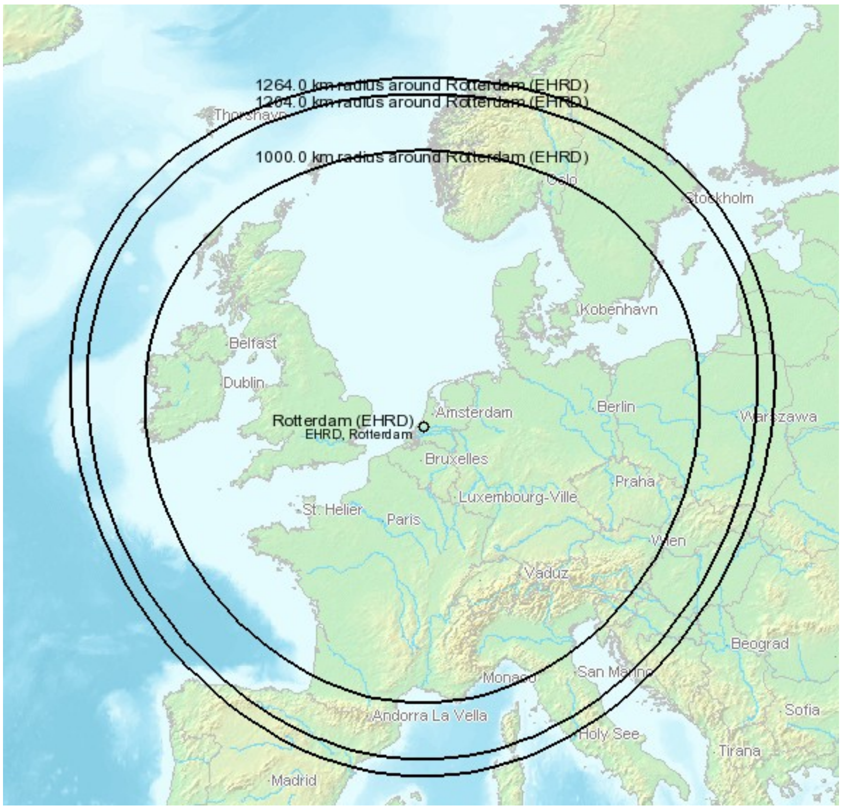

Figure 13.3: Range map of the InfiniCraft

Chapter 14 | Fuel Life Cycle Analysis

In this chapter the life cycle analysis (LCA) of different sources for ethanol production will be discussed. The LCA is a tool to compare different fuel sources and see their impact on the environment. Making a LCA is a long and difficult process, therefore the LCA for ethanol made from corn, sugarcane and switchgrass is based on the PhD thesis of Lin Luo [31]. The LCA for ethanol made from waste is based on a study made by the chemistry department at the Texas A & M University [32]. This chapter starts with an introduction to the LCA and ends with a conclusion and an example. The detailed discussion of the life cycle analysis of the different ethanol sources can be found in appendix A.

14.1 Introduction to the Life Cycle Analysis

The life cycle analysis gives an overview of the events that occur during the growth, production and usage of a product, in this case ethanol. This means a complete overview will be made of the processes that occur during the production of ethanol. This will of course differ for each source that is used (like corn, switchgrass, etc.) so these will be explained separately. One remark that needs to be stated here is that the graphs and numbers are based on "the energy that is needed to power the wheels of a car for driving one kilometer." This is however no problem, because the different fuel sources will be compared relatively to each other and they can be scaled for an aircraft. For every fuel source the following things will be discussed. First the life cycle of the fuel will be described, so a good overview of the processes can be obtained. Afterwards the land use will be calculated. Here it can be seen how much land is required to fuel an airplane for one year. The last thing that will be explained is the environmental impact of making ethanol. Here will be looked at the global warming potential (GWP), the ozon layer depletion potential (ODP) and the toxicity potential (TP). Finally all fuels will be listed and compared.
A final remark that needs to be made is that in the thesis [31], gasoline was compared with E10, E85 and E100. In this report, gasoline will only be compared to pure ethanol (E100) because this fits better in the Cradle to Cradle® concept.

14.2 Discussion of the Results

A comparison of the methods to make ethanol is shown. The options will be compared to normal gasoline and the benefits and disadvantages will be explained. Because of the fact that the LCA of corn, sugarcane and switchgrass were part of the same paper, they will be compared relative to each other and afterwards ethanol made from waste will be compared to the rest. The graph from the thesis [31] is shown in figure 14.1. In this graph, also bio-mass is included. Like defined earlier, this is part of the option "waste". This means bio-mass will be included in the first comparison, while municipal solid waste will be discussed afterwards.

14.2.1 Environmental Impact

In figure 14.1 the overall comparison of the ethanol fuels can be found. The most important environmental impacts will be discussed here. One of the most important impacts is the GWP. In this graph it becomes clear that the statement "biofuels (ethanol) are good for the environment" is not always true. It really depends on the source for the ethanol. For example ethanol made from switchgrass has a positive influence on the GWP (compared to gasoline). However, ethanol made from corn or biomass has a negative influence on the GWP. This is because of the high amount of energy that needs to be added to the process. Also the process itself emits a lot of CO_2. The CO_2 emissions of ethanol made from sugarcane lies somewhere in between the emissions of the other fuels. So if only the GWP is taken into account, ethanol made from switchgrass is the best option.
In general it can be seen that all biofuels do better on abiotic depletion potential (ADP), ozone depletion potential (ODP) and acidification potential. This is because these factors are mainly influenced by the emissions produced when working with crude oil (for further and detailed explanation the thesis from Lin Luo can be consulted [31]). Furthermore it can be seen that biofuels are doing worse on the photochemical oxidation potential (POCP), toxicity potential (TP) and eutrophication potential (EP). This is mainly because of the disadvantages of growing crops. Chemicals need to be used and emissions are produced during the process of growing and processing the crops.
The last comparison that will be made is the comparison of gasoline with ethanol made from waste. This is not a straight forward comparison. On one side, this fuel does not absorb CO_2 during the process of growing the fuel source. This means it is not like the other ethanols and it is as polluting as gasoline. However, the process of

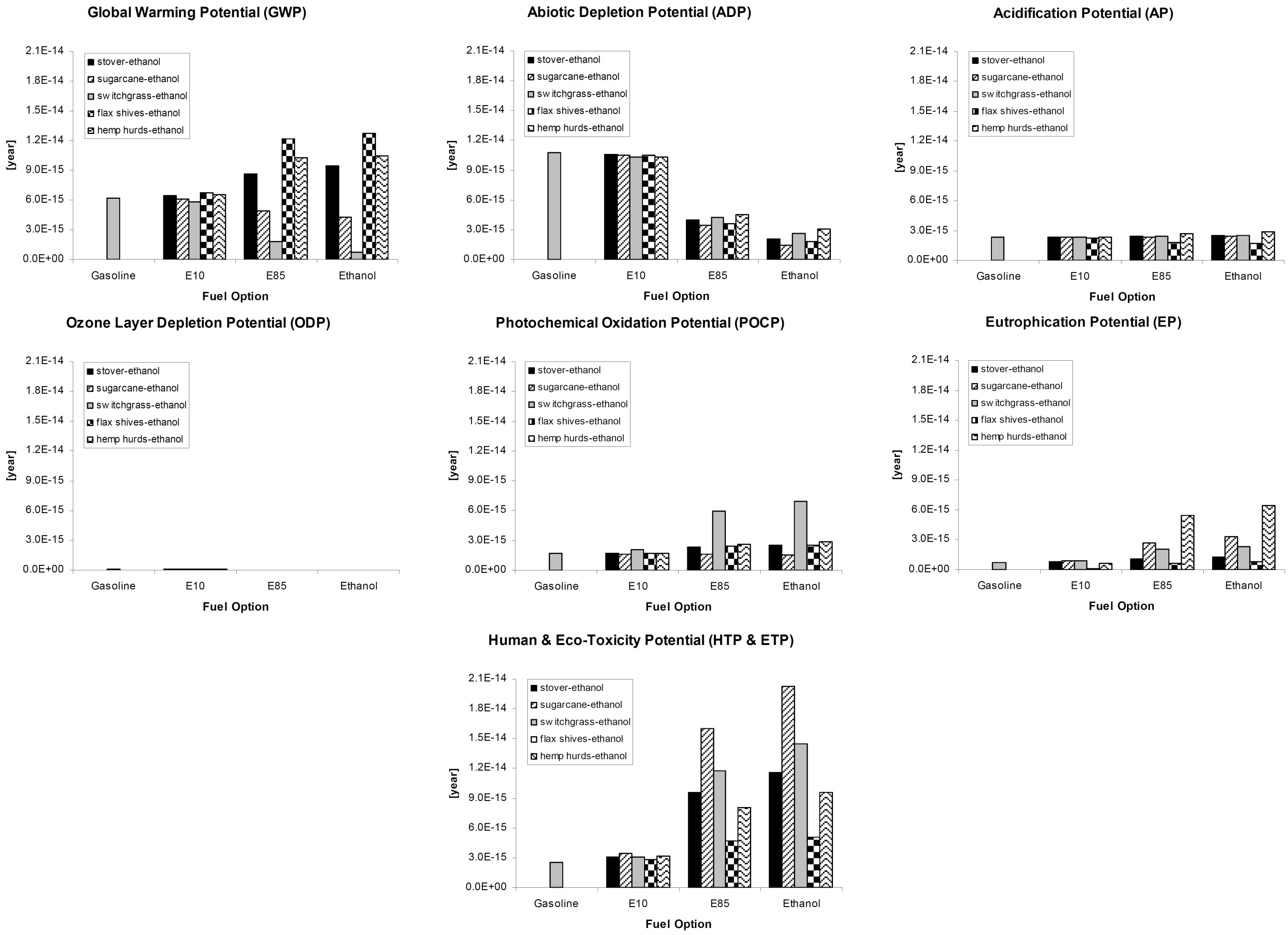

Figure 14.1: Overall comparison of environmental impact of all fuel options [31]

making the ethanol is better than making gasoline from oil, so here this fuel seems to be better again. Also, it can be stated that if the waste lays on the landfill it will produce methane and other gases. Those gasses are 25 times worse than CO_2 [33] and so it can be concluded that making ethanol from waste is better for the environment. This means that the more the aircraft is flown, the better it is for the environment.

14.2.2 Land Use

Each source for ethanol needs a different amount of land to grow on. In table 14.1 the land use per aircraft per year is given.

Table 14.1: Land use

Source	**land/aircraft/year**
Corn	71 578 m^2
Sugarcane	19 813 m^2
Switchgrass	26 403 m^2
Waste	0 m^2 *

*: Waste does not use land to grow on, so this is noted down as 0 m^2

It can be seen that sugarcane uses the least amount of land, followed by switchgrass. Corn uses much more land (almost 3 times more than switchgrass), which is not attractive. Also, switchgrass can grow on places where no food grows, which is another plus for this source.

14.2.3 Conclusion

Picking one specific type of biofuel is very difficult since they all have their benefits and drawbacks. Overall switchgrass looks like a good solution: it can grow on places where no food can grow and it does not require a lot of energy and chemicals to grow. However, it is not very sustainable to choose one source. It is better to make sure different sources are picked, especially when a larger number of aircraft will be sold. An exception is the ethanol made from waste. It produces more CO_2 than the other ethanol fuels but it can be stated that the waste would produce emissions that are worse than CO_2 when nothing would be done with it. This means this method can also be seen as Cradle to Cradle®.

14.2.4 Practical Example

From the life cycle analysis (LCA) of ethanol derived from corn, switchgrass, sugarcane or waste it is known that a certain amount of land or kg of waste is needed to fly the InfiniCraft for one year. In this subsection the following question will be answered: "What will happen if all the aircraft on Kempen airport will be propelled using ethanol?" This practical example is given to assess the feasibility to propel most of the general aviation with ethanol.

Kempen Airport, which is located in Budel, is a general aviation airport in the south-east of the Netherlands located 5 NM (9.3 km) west of Weert and near the border with Belgium. Its main runway, 03/21, is a 1 199 m (3 934 ft) long asphalt runway. There is a second runway for microlight aircraft only, located next to the main runway, and is 600 m (1 969 ft). On a yearly basis about 80 000 movements are made on the airport, landing or take-off. [34] As a comparison, in 2011 437 000 movements were registered on Amsterdam Schiphol airport [35]. On a yearly basis 300 m^3 of avgas is used on Kempen airport to fuel small airplanes. It is know that ethanol has a lower energy density than avgas but it is also known that the fuel consumption of ethanol driven engines is lower than avgas driven engines [26]. Therefore, it will be assumed in this example, that 300 m^3 of ethanol will be needed on an annual basis.The source of the ethanol: corn, switchgras, sugarcane or waste must be selected based on the location where it will be used. Since there is no place in the Netherlands for extensive land use for ethanol, the assumption is made to use waste to make the ethanol from.
From appendix A.4, dealing with the LCA of ethanol derived from waste, it is know that:

- In order to make one 1 litre of ethanol 2.11 kg of waste is needed.
- On average each inhabitant of the Netherlands produces 500 kg of waste on a yearly basis.

This yields that 633 000 kg of waste is needed on a yearly basis for Kempen airport. This means that the waste of 1 266 people is needed. Budel for example has about 9 000 inhabitants, which means this could be a self sustaining airport [36].

Chapter 15 | Engine Specification

Based on the power loading diagram, chapter 8, an engine power of at least 103 hp is needed for take-off. This is based on the power-to-weight ratio from the loading diagram and the MTOW from the weight estimation.

15.1 Engine Selection

Currently there are only a few certified engines specifically designed for the use of E100 fuels. Instead of designing a whole new engine however, existing engines running on 100LL or 91 avgas fuels are converted for the use of ethanol. This is thermodynamically possible, but a downside of this is that these engines need to be re-certified. The carburettor needs to be changed as ethanol has a richer fuel to air ratio, requiring a higher fuel flow to the cylinder. Furthermore different fuel line and fuel tank materials need to be used to withstand the degradation from the ethanol. Finally the optimal compression ratio of ethanol is 12:1, while avgas, depending on the octane content, runs from 7:1 to 10:1 for mogas and 100LL respectively (with supplemental type certification for mogas, due to danger for knock).

Four engines from major manufacturers are evaluated based on their engine power rating and high compression ratios for convertibility (see table 15.1).

Table 15.1: Selected engines for convertibility

Parameter	**LycomingO235 [37]**	**Rotax914F [38]**	**ContinentalO200 [39]**	**Rotax912ULS [40]**
Power [hp]	125 hp 2800 rpm	115 hp 5800 rpm	100 hp 2750 rpm	95 hp 5500 rpm
Weight [kg]	113	75.5	64	56.6
Comp. ratio [$-$]	9.70:1	9.0:1	8.5:1	10.5:1
Suitable fuel	100LL/100	87,91,100LL	81,87,91,100LL	91,100LL/100
Price [$]	17 450	31 679	25 344	14 864

It can be seen that the engines differ in compression ratio ($8.5 - 10.5$), price ($\$\,14\,000 - \$\,31\,000$) and weight ($56.6 - 113\,kg$). Since the engine becomes more efficient close to a high compression ratio of 12, the continental engine is not chosen, because of its fuel economics. The next choice depends on the relative value of weight and money. The Lycoming and Rotax 912 ULS engines are cheaper, but the Lycoming engine is 37.5 kg heavier than the Rotax 914 engine. Therefore the Rotax 912 ULS engine is chosen. This engine is lighter and cheaper than the Rotax 914 and Lycoming engine. Since the use of ethanol will change the nameplate power of the engine, the Rotax engine power needs to be evaluated, because using avgas, the nameplate power is 8 horsepower below the requirement of 103 already. Furthermore this engine has a higher rpm with gearbox, giving more higher frequency noise, which needs to be evaluated.

15.2 Engine Evaluation

For the evaluation of the Rotax 912 ULS engine on Cradle to Cradle® characteristics, first the thermodynamic engine characteristics are evaluated using a numerical calculation. Then the fluids and materials needed during the operative time of the engine are evaluated on the Cradle to Cradle® characteristics. Last the engine end-of-life is explained.

Engine characteristics with E100

The Rotax engine works on an Otto cycle, commonly named a 4-stroke engine. The thermodynamic cycle comprises of adiabatic compression and expansion and isochoric heating and cooling. For the calculation the standard theoretic thermodynamic formulas for the Otto cycle are used together with the engine and fuel specification and efficiency assumptions to get a realistic value from the theoretic thermodynamic calculations. The engine data is retrieved from the Rotax 912 ULS manual, the fuel data from the US government Alternative Fuel Data Centre and the efficiency assumptions are based on MIT course 8.21 Physics of Energy Otto cycle measurements [41]. This leads to the following parameters in tables 15.2 and 15.3.

Table 15.2: Input parameters

Parameter	Value
Ethanol density [g/L]	790
Universal gas constant [J/kg]	8314.4
Number of cylinders[$-$]	4
Cylinder bore [m]	84e-03
Piston stroke [m]	61e-03
Compression ratio [$-$]	10.5
Intake pressure [Pa]	101e+03
Intake temperature [K]	298
Intake manifold temperature [K]	360
Exhaust pressure [Pa]	108e+03
Volumetric efficiency [$-$]	0.88
Mechenical efficiency [$-$]	0.82
Combustion efficiency [$-$]	0.95
Fuel heating value [J/kg]	26.9e+06
Air/fuel ratio [$-$]	9
Molecular weight ethanol [g/mol]	46.07
Ratio of specific heats [$-$]	1.26
Conversion tolerance [$-$]	1e-04

Table 15.3: Engine specifications

Parameter	Value
Engine efficiency [$-$]	0.40
Fuelflow at 2700 rpm [L/hr]	25.5
Brake power at 2700 rpm [hp]	80.72
Fuelflow at 3450 rpm [L/hr]	32.5
Brake power at 3450 rpm [hp]	103.15
Spec. fuel consumption [g/kWh]	334.1
Exhaust temperature [C]	1489.4
TBO [hr]	2000

Using a numerical approach, the power [hp], torque [Nm] and fuel flow [$^L/_{hr}$] trend compared to the engine speed [rpm] for the Rotax 912 ULS engine on ethanol can be iterated. This generates figure 15.1. It can be seen that the power and fuel flow linearly depend on the engine speed. This is a theoretic limitation of the calculation, since real life engine measurements will show a curved relation. As for the torque, the calculation shows constant torque, also this is an approximation, real life measurements will show a more curved concave function. The graph is stopped at 5 500 rpm. This is the maximum speed of the engine using avgas. However this would be different with ethanol. Therefore the maximum rpm is set to the 103 hp requirement, which gives 3 450 rpm. It would be safe to state that this would be the maximum rpm of the engine, while this is 2 000 rpm under the avgas limit, since calculations are not done on maximum engine speed. Hence a large safety bandwidth is needed and further research can redefine this limit in a later stage.

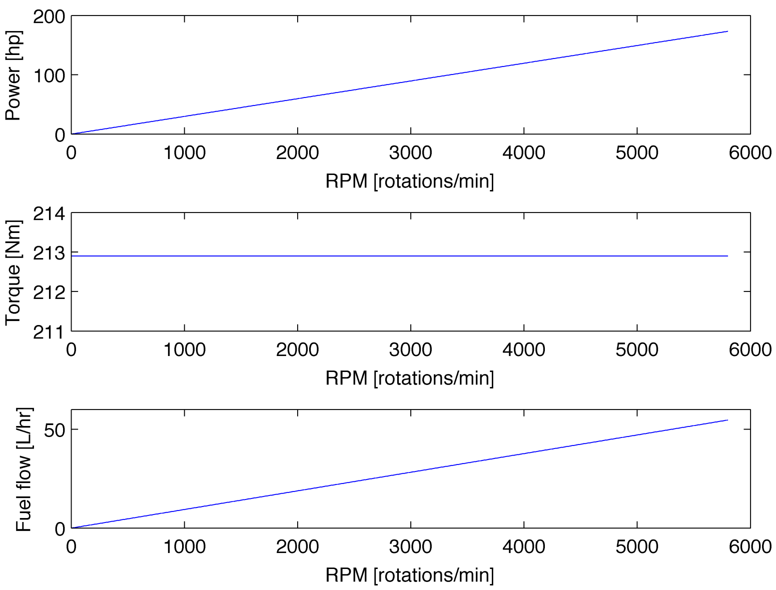

Figure 15.1: Thermodynamic characteristics Rotax 912 ULS running on ethanol

Engine usage

The recyclabilty of parts and fluids needed during engine usage will be discussed in this part.

One of the fluids needed is antifreeze. For this NPG+ coolant is used which consists out of ethylene glycol and propelene glycol. Recycling of these substances can be done by removing contaminants such as emulsified oils and heavy metals either by filtration, distillation, reverse osmosis, or ion exchange. Another option is restoring critical antifreeze properties with additives. Additives typically contain chemicals that raise and stabilize pH, inhibit rust and corrosion, reduce water scaling, and slow the breakdown of ethylene glycol, however this is not preferred over filtering [42]. One of the major aspects of NPG+ coolant is that it lasts the lifetime of the engine and does not evaporate or needs to be changed. Therefore complete recycling is possible. The costs per gallon of ethylene glycol recycling, the main constituent of NPG, is $ 0.26. [43]. This is based on batch recycling, which is the recycling of large volumes of coolant to get economies of scale. Adding to this the separation of ethylene and propylene glycol and initial filtering of $3 per gallon, the recycling of propylene glycol $ 0.72 per gallon and the mixing of constituents to NPG+ at $ 0.40 per gallon, the total costs of recycling are $ 3.80 per gallon [44]. This falls within the selling price of NPG+ at $ 34.64 per gallon[45].

Engine end- of- life

Data on the recycling of the Rotax 912 ULS engine is scarcely available, however the US environmental protection agency has done research on comparable 2-stroke marine engines and their recyclability. The research showed most 2-stroke engines consisted of an aluminium frame and engine block (80.9%), steel crankshafts and power output shafts (10.1%), copper for wiring (5.2%) and only 3.6% of plastic [46]. The research concluded that the amount of metals make it possible to economically recycle them by crushing the engine into little pieces (no disassembly) and using a magnet to separate. However the plastics cannot be technically or economically recycled due to their limited, but distributed size. The plastics in the engine are therefore a point of interest for the Cradle to Cradle® design.

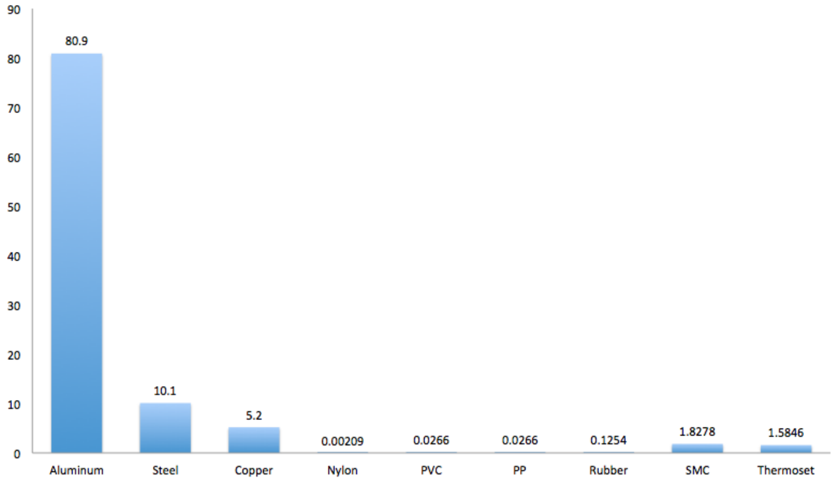

Figure 15.2: Material breakdown of a 2-stroke marine engine

Since the overhaul cost after 2 000 hours of a Rotax 912 ULS engine lies between $ 10 000 – $ 12 000, the owner is rationally willing to pay an amount lower than this for swapping his engine for a new engine, e.g. $ 9 999 (some individuals might be willing to pay more, since they get a new engine, instead of a revised engine). The willingness to pay lies under the selling price, hence $ 4 865 needs to be earned on the returned engine to make this economically worthwhile for the manufacturer (assuming the selling price has a profit margin). The engines therefore needs to be sold for at least $ 4 865 to experimental aircraft users or other industries, like the automotive industry. Since the figure shows that the engine consists for 96.4% out of recyclable materials, re-using the engine on a lower quality level before scrapping the engine is still within the Cradle to Cradle® philosophy.
The remaining important factors for recycling are the engine coatings, cleaning the engine before scrapping and 'plausible' Cradle to Cradle® plastic replacements.

The 912 ULS Rotax maintanance manual shows the use of coatings on the following parts [47]:

- Cylinder wall: NICKEL-SILICON
- Sprag clutch: LOCTITE 221
- Propeller shaft: LOCTITE 221
- Disc springs: LOCTITE 221
- Disc dogs: LOCTITE 221
- Gear unit: LOCTITE 221

These coatings therefore need to be sanded off before being able to scrap the engine. This results in a small loss of material and gives a small portion of non-recyclable material.

Chapter 16 | Engine Noise Analysis

Noise regulations in FAR part 36 include requirements on noise. These requirements are described as follows: "The take-off noise is defined as the noise measured at a distance of 21 325 ft (6 500 m) from the start of the take-off roll, directly under the airplane". This corresponds to a measurement point after the runway as visualized in figure 16.1. Here the noise is not allowed to surpass the limit of 62 dB.

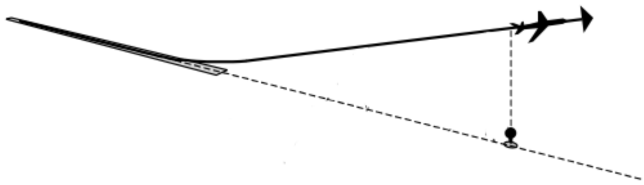

Figure 16.1: Noise measurement position

Using the INM noise database [48] the required minimum height (or distance) over the measurement point can be determined to meet the 62 dB requirement. For this, the noise ID of a similar aircraft, Cessna 172, is chosen at maximum power during take-off. This gives the following noise profile from figure 16.1.

Table 16.1: Noise profile Cessna 172 [48]

height [ft]	200	400	630	1 000	2 000	4 000	6 300	10 000	16 000	25 000
Noise [dB]	84.6	77.8	73.2	68.2	60.4	52.0	46.2	39.9	33.5	25.6

Looking at the table the aircraft needs to be at a height of 2 000 ft or 609.6 m when passing the measurement point to meet the noise requirements, which lies at a distance of 6 500 m from the beginning of the runway take-off point. With the maximum take-off distance requirement of 500 m and the 609.6 m measurement height to fulfil the 62 dB noise requirement the required theoretical climb gradient can be determined. The measurement point lies 6 000 m after the aircraft clears the ground, this means the climbing gradient needs to be 0.101, which corresponds to a flightpath angle of 5.8 degrees.

The maximum climb rate from requirements is 5 m/s and take-off speed is 34.5 m/s as both determined in the initial sizing. This gives a maximum flightpath angle of 8.33 degrees, which falls within the required flightpath angle for this aircraft for noise.

Furthermore, the Rotax engine will work with a higher rpm shaft speed than the Cessna 172, namely 3450 rpm instead of 2 400 rpm. This does not apply to the propeller speed, since the Rotax engine uses a gearbox system to keep the propeller speed similar to that of the Cessna 172. Higher engine speeds lead to a higher frequency noise, but not to a higher decibel noise, contrary to the propeller speed, which also shows an increase in decibel. Higher frequency noise is perceived to be less pleasant, but is not stated in any requirements or regulations.

The noise profile from the INM database uses a 2 blade fixed pitch propeller. The choice between a two, three or four propeller configuration therefore, influences the current noise output of 60.4 decibel at 2 000 ft. The trade-off depends on the noise generated by the propeller, the weight and the efficiency of the propeller.

Miljkovic et al. (2012), showed that the noise in decibel for a two blade Cessna 172 compared to a three blade Cessna 172, is 0.5 to 2 dB higher depending on the propeller speed [49]. This can be seen in figure 16.2. Apart from the decibels however, they also investigated the human noise preference and concluded that the noise of the two blade propeller was preferred over the 'quieter' three blade propeller, because of its lower frequency, which is perceived by the human ear as less intrusive.

RPM	Cessna 172N Two-blade propeller	
	Noise Level L_{Aeq} dB(A)	Articulation Index (AI)
900	69,5	0,45
1500	82,3	0,28
2400 TO/GA	93,3	< 0.20 (0.15)*
RPM	Cessna FR172F Three-blade propeller	
	Noise Level L_{Aeq} dB(A)	Articulation Index (AI)
900	69,0	0,45
1500	83,0	0,28
2400 TO/GA	91,0	< 0.20 (0.17)*

Figure 16.2: Noise two and three propeller configuration Cessna 172

RPM	Propeller blades	Preference
900	2	15 (94%)
	3	
	NDD*	1 (6%)
1500	2	10 (63%)
	3	6 (7%)
	NDD*	
2400 TO/GA	2	12 (75%)
	3	4 (25%)
	NDD*	

*NDD - Not Discernible Difference

Figure 16.3: Human noise preference

NASA did a comprehensive literature study in 1995 concerning the choice of 3,4 or 5 blade configurations, compared to a 2 blade configuration. The conclusion was that 3, 4 and 5 blades give a reduction in noise of respectively, 4 dB, 8.5 dB and 13 dB [50]. However the thrust is reduced due reducing the propeller diameter, while increasing the number of blades, by respectively 0.75%, 1.5% and 2.25%. Also the weight increases with 5 kg with each added blade, due to the structural integrity requirements and the added blade. Therefore three blades are chosen, which give a noise reduction without inceasing the weight and decreasing the thrust too much.

16.0.1 Noise Fees

Another important aspect of the noise production of the aircraft is its influence on the landing fees. Today's landing taxes of aircraft are partially based on the aircraft's noise certificate. Even though noise legislation for the aviation industry is different in every country, the current analysis on the Dutch legislation can be used as an indication for worldwide operations of the InfiniCraft. Currently the Dutch legislation identifies eight categories for aircraft, depending on their noise certificate, which can be seen in table 16.2.

Table 16.2: Dutch general aviation noise regulation (chapter six)

Noise category	**Noise range** $[dB]$
1	> 78
2	75 - 78
3	72 - 75
4	69 - 72
5	66 - 69
6	63 - 66
7	60 - 63
8	< 60

As one can see from the table above, the eight category consists of all aircraft producing less then 60 dB. As the current noise estimation of the InfiniCraft estimates a total noise production of 60.4 dB, only minor noise fee increments will be set for the aircraft. However, looking at some of the most used general aviation aerodromes in the Netherlands, both the seventh and eight category obtain the same landing fees [51] [52] [53]. This means that the InfiniCraft will always obtain the lowest possible landing fees, which is beneficial for the operating costs.

Chapter 17 | Emergency Solution

In aviation industry, safety is a very important point of focus. Therefore, safety equipment is needed to comply with all the regulations. However, some new techniques are developed to increase the safety even more. A few of these methods will be discussed in this chapter. This section will consist of two parts. First, all of the on-board emergency equipment will be listed. Next to this equipment list, a second part will look at possible emergency solutions in the case of an in-flight shut down (IFSD).

17.1 Emergency Equipment

According to the EASA/FAA requirements, the emergency equipment can be categorised in the following three categories:

- **Emergency Locator Transmitter (ELT), Personal Locator Beacon (PLB):** In the case of an emergency landing, emergency services have to be informed. Both ELT's and PLB's can be used for this function. Both ELT's and PLB's are radio beacons which can manually be activated and are automatically activated in case of crash detection. They play an important role in the search and rescue operations on aircraft crashes in remote areas. Even though EASA nor FAA have specific requirements on the use of ELT's and PLB's, the aircraft will be fitted with an ELT as several countries require ELT carriage for all aircraft flying within their airspace.
- **Fire extinguishers:** In case of a fire, standard fire extinguishers such as carbon dioxide and dry chemicals can not be used in aircraft. They would damage the aircraft structure, reduce the visibility and absorb all of the oxygen around the fire, which would create a dangerous situation in a small space such as the cockpit. Instead, Halon extinguishers will be used. Their environmental impact, availability and its low (but still present) toxicity are Halon's main drawbacks. Still Halon is assumed to be the best solution in aviation. [54]
- **Floating devices:** If the aircraft is used in over-water operations, floating devices have to be onboard the aircraft. According to regulations, life jackets have to be present in case an over-water flight is performed beyond the gliding distance to the coast according to the aircraft's altitude. For ease of operations those life jackets will be onboard of the aircraft permanently. As an option, life rafts can be implemented into the emergency equipment if customers are planning extended over-water operations.

17.2 Other In-flight Solutions

In case of an unrecoverable emergency, some options exist that might be able to save the passengers. Some of them are very easy to implement, other require some major design changes.

- **Seatbelt airbag:** A modern solution to reduce injuries is to put an airbag in the seatbelt (see figure 17.1) of the airplane. Companies like Amsafe [55] develop some hightech devices to implement in general aviation aircraft. The airbag itself is folded into the seatbelt and a crash sensor and small gas tank are installed in the aircraft. The crash sensor measures impacts in the horizontal plane and deploys the airbag when it feels a crash. The airbag deploys from your lap to your face. In this way it makes sure you do not get pushed into your seat, which can have extra injuries as a consequence. Since the sensor only measures impacts in the horizontal direction, turbulence and hard landings will not trigger the airbag. Overall this sounds like a very good and rather cheap solution to reduce the chance of injuries during an impact.

Figure 17.1: An Amsafe seatbelt airbag for general aviation [56]

- **Parachute recovery system:** Another option is the recovery parachute (see figure 17.2). Such a parachute system is on the market already, the Ballistic Recovery System. This certified system consists of a parachute that deploys when certain accelerations are exceeded. It can be used in all kinds of emergency, from loss of control to total in-flight breakup. The system can be installed on different kinds of aircraft and has already saved about 250 lives [57]. It is for example used on Cirrus aircraft. A rocket is used to unfold the parachute when the system is triggered. The parachute will then unfold and decrease the downwards velocity of the aircraft. This makes sure the aircraft can come down in a safe way while the pilot has more change to survive. This looks like a promising system, but it will require some more adaptions than for the seatbelt airbag. Also the costprice and the extra weight will be a limiting factor. However, reducing the possibility of a complete loss of the aircraft during a crash, the parachute recovery system contributes to a better implementation of the Cradle to Cradle® philosophy within the InfiniCraft.

Figure 17.2: Picture of the parachute system of a Cirrus aircraft [58]

PART IV

STRUCTURES & MATERIALS

"What is important is what you do with the material and, in particular, how you treat it"

Olivier Malavallon,

PAMELA-Life project director

Chapter 18 | Aluminium Analysis

From the trade-off presented in chapter 7, it was concluded that the primary structure of the aircraft would be made completely from aluminium. This chapter will present an analysis on the feasibility of using automotive aluminium alloys in the aerospace industry, as this would greatly enhance the recycling capabilities of the design. In appendix B, Al-6022 has been selected from the automotive alloys to be used for the structural design. In order to make a well-considered material choice, three alloys are compared with each other, Al-6022, Al-7075 and Al-2024. Al-6022 is currently used in the automotive sector and will be the main focus of the research.

18.1 Material Properties

Before doing a more thorough analysis on the 6022 alloy, first an assessment is done on the material properties of the respective alloys. This analysis includes a strength, density, elasticity, crack propagation, price and corrosion analysis. Since more research should be done on the 6022 alloy, a comparable alloy (Al-6013) is used to obtain data on fracture toughness and the corrosion rate. As different heat treatments are applied to the material to obtain slightly different mechanical properties, it is important to mention it for the alloy. The typical aerospace alloys together with their heat treatment are Al-7075-T6 and Al-2024-T3. For this comparison Al-6022-T4 will be used.

Table 18.1: Mechanical Properties Comparison of Al-6022, Al-7075 and Al-2024

	Al-6022-T4 [59]	**Al-7075-T6 [60]**	**Al-2024-T3 [61]**
Ultimate tensile strength $[MPa]$	271	572	448
Tensile yield strength $[MPa]$	160	503	310
Density $[kg/m^3]$	2 700	2 810	2 780
Young's modulus $[GPa]$	68	71.7	73.1
Fracture Toughness [62] $\left[MPa\sqrt{m}\right]$	40	33	38
Price [62] [€/kg]	6	7.2	7.4
Corrosion rate [63] [64] $[mm/year]$	0.11	0.16	0.15

Immediately, one can see significant differences in material properties between the three alloys. Below, a summary is given on the advantages and disadvantages of Al-6022 with respect to the aerospace alloys.

Advantages

- **Lower material price:** The use of Al-6022 can reduce the total manufacturing cost of the aircraft as, according to the materials department of the faculty, the alloy is cheaper compared to typical aerospace alloys.
- **Better corrosion resistance:** The 6022 alloy has been designed specifically for better corrosion resistance. From table 18.1 it can be seen that the 6022 alloy shows a lower corrosion rate than the other alloys. It should be noted that the presented values are computed for bare material. This means that in the end, less coating material will have to be used, which benefits the Cradle to Cradle® philosophy of the aircraft.
- **Better formability:** The 6022 alloy is designed specifically for good formability, which makes Al-6022 to obtain better formability, compared to typical aerospace alloys.
- **Lightweight:** Al-6022 is less heavy than the 2024 and 7075 alloys. It should be noted however that this advantage may be reduced as the structure will become heavier due to the reduced mechanical properties of Al-6022.

Disadvantages

- **Reduced mechanical properties:** The main disadvantage of the 6022 alloy is its reduced mechanical properties in comparison to typical aerospace alloys.
- **Aerospace structural design:** The structural design in the automotive sector mainly focusses on crash protection. Even though this is an important aspect in the automotive industry, aircraft structural puts more effort specially at crack propagation and maintenance inspection interval analysis. In order to implement Al-6022 within the Cradle to Cradle® aircraft design, one has to investigate on those key factors.

- **Fracture toughness:** The 6022 alloy performs less well in crack resistance. Due to its low fracture toughness, cracks might grow faster and larger than the Al-7075 and Al-2024. A more detailed description on this parameter will be given later in this chapter.

18.2 Fatigue Behaviour

Crack sensitivity and propagation are important design characteristics of the aircraft structure. Therefore, the fatigue behaviour of materials is a key element within aircraft design. One of the issues with the 6000 alloys, identified in section 18.1, is its reduced fatigue properties. This is mainly because of the low importance of fatigue failure in the automotive industry. For the same reason the 6000 series alloys lack detailed fatigue data. Still it is important to analyse the very basic fatigue properties of Al-6022, which will be done in the first subsection. Fatigue life estimates can be calculated in three different ways: stress-based analysis, strain-based analysis and the fracture mechanics approach [65]. The next part of this section will show the calculations for a stress-based analysis of the Al-6022 fatigue behaviour.

18.2.1 S-N curve

One method of identifying the fatigue behaviour of a material is the stress-based analysis. This method consists of a number of fatigue tests where a sample is put under a cyclic loading at different stress levels. The output from this analysis is the so called Wöhler curve or S-N curve. It plots the allowable stress amplitude for material failure as a function of load cycles. This curve can be created both from material sample testing as well as analytical calculations. Those tests performed on actual structural components will deliver more detailed data about the fatigue behaviour of the aircraft. However, within the context of the project, only an estimated S-N curve will be created and this for the case of an unnotched sheet of Al-6022. All of the calculations shown below are performed in accordance with the book of Schrijve [66]. The fatigue behaviour of a material depends on two properties of the load case: the stress ratio, R, and the mean stress, σ_m. The stress ratio is the ratio of the maximum and minimum stress of the loading. The mean stress is the average stress around which the stress amplitude oscillates. Both properties can be identified in figure 18.1.

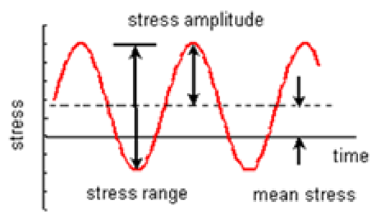

Figure 18.1: Stress amplitude and mean stress visualisation [67]

Figure 18.2 shows the resulting S-N curve. The curve shows the specific case for which the mean stress of the loading is equal to zero and the stress ratio -1. If the properties of the load case would change, different fatigue behaviour would be found. However, within the context of the comparison study of Al-6022 with typical aerospace alloys, only this most general case is sufficient.

- **0 - 100 cycles:** In the preliminary phase of the structure, the aluminium will only fail if a total stress amplitude is applied which is equal to the ultimate strength of the alloy itself. According to Schrijve [66], aluminium alloys can resist this ultimate stress up to 100 cycles after the initiation of the load.
- **100 - 1 000 000 cycles:** After the initial phase of the cyclic loading, the total allowable stress amplitude for the aluminium before failure will start to reduce exponentially. As the S-N curve is plotted by convention on a log-log scale, this phase becomes a linear relation on the graph.
- **> 1 000 000 cycles:** For aluminium alloys, once the structure has been loaded more than a million times, the stress amplitude which the structure can resist before failure becomes almost constant. This stress amplitude is called the fatigue stress of the material. Again for aluminium alloys, the fatigue stress of a material is approximately equal to 0.4 times the ultimate stress. In the case of Al-6022 T4 this stress equals 108 MPa.

Looking at the requirements in chapter 3 however, the aircraft has to be designed for 12 000 cycles. However, considering the fact that the 6022 alloy has reduced mechanical properties, the design shall be designed to last for 15 years, e.g. 6 000 cycles. For certification regulations, this amount of cycles has to be multiplied by a safety factor. For stress-based fatigue calculations a factor of eight has to be added. Multiplying this amount with a factor of 8 yields a lifetime of 48 000 cycles. Vibrations on the wing can be neglected when the stress ratio of the S-N curve is set to be -1.

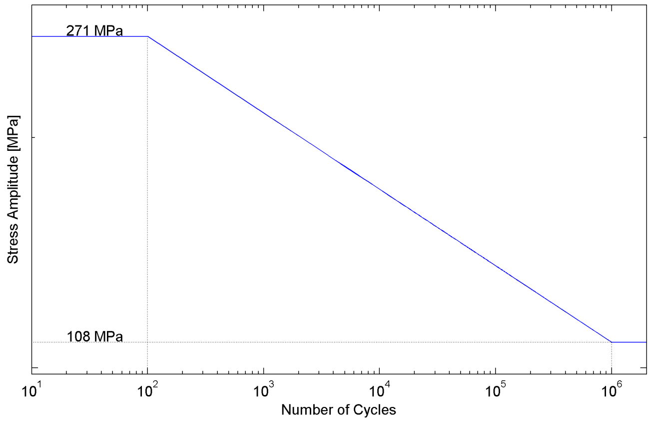

Figure 18.2: S-N curve for 6022 T4E29

Table 18.2: Fatigue limit, unnotched, 1 000 000 cycles

Specimen	**Fatigue limit** [MPa]
Al-7075-T6 [60]	159
Al-2024-T3 [61]	138
Al6022-T4	108

18.2.2 Limitations of the Current Fatigue Analysis

The fatigue analysis performed in the previous subsection will be used as input for the structural design of the aircraft and as a general comparison with Al-7075 and Al-2024. However, one has to keep in mind some crucial shortcomings in order to perform a detailed structural design.

- **Mean stress equals zero:** The assumption that the cyclic loading is centred around a mean stress of zero provides the highest possible S-N curve. The exact relation between the allowable stress amplitude and the stress ratio can be seen in figure 18.3. Therefore, in case of a different loading, the fatigue properties of the Al-6022 structure will be lower.

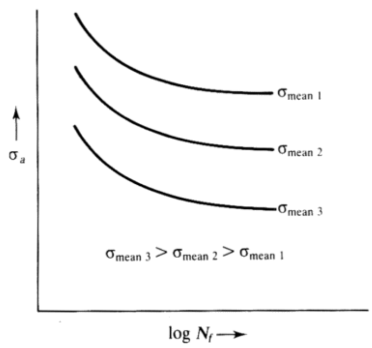

Figure 18.3: Influence of the mean stress on the fatigue behaviour of materials [68]

- **Notched structures:** The actual structure will contain several cut-outs to accommodate for wiring and fasteners. Stress concentrations around those cut-outs will be higher compared to the structure itself. In order to compensate for this, the design life cycles was multiplied with a factor of 8, in order to determine the fatigue limit of the material at the desired design point.

18.2.3 Fatigue Strength Design Point

Using fatigue data from CES Edupack [62], it was determined that the fatigue strength of the 6022 alloy at 48 000 cycles is 126 MPa. The structure will be sized according to this design strength.

18.2.4 Crack Propagation

Another important parameter in the fatigue analysis is the fracture toughness of the material. Alloys that are currently used in the aerospace industry all have reliable crack propagation properties, such that a good prediction can be made on crack growths. In order to apply the 6022 alloy in the design, a thorough analysis should be made on the crack propagation of this alloy. The K_{1c} value is obtained via testing, of which the basics are shown below in figure 18.4 [69].

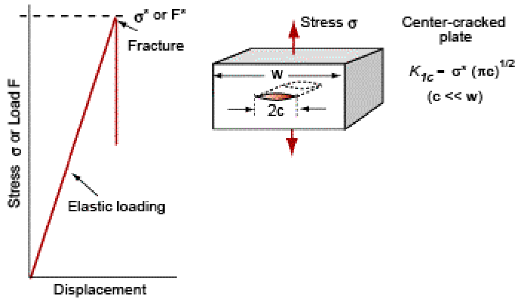

Figure 18.4: Crack propagation measurement [69]

The fracture toughness, or the K_{1c} value, of a material is then defined by equation 18.1, in which Y_1 is the geometry factor of the tested sample.

$$K_{1c} = Y_1 \sigma \sqrt{\pi c} \tag{18.1}$$

High K_{1c} values yield high crack growth resistance at certain stress levels. For this reason, high K_{1c} values are desirable for the aerospace industry [14]. Looking at the material properties in table 18.1, one can see that the 6022 alloy has a comparable K_{1c} value to Al-2024. It is however recommended to perform tests on the material as a slightly worse fracture toughness would result in an increase in inspection intervals, and maintenance costs.

18.3 Coatings

In the baseline report [14], the conclusion was made that aluminium could fit well within the Cradle to Cradle® philosophy. However, coatings are required to protect the aluminium from degradation. Those coatings used today are still a major challenge to make aluminium structures environmental friendly. In this section possible solutions for this problem are analysed. First, anti-corrosion coatings will be analysed, thereafter paintings will be treated.

18.3.1 Anti-Corrosion Treatments

Even though Al-6022 has a better corrosion resistance compared to typical aerospace alloys, anti-corrosion coatings are still required in order to keep the aircraft structure free from corrosion degradation throughout its operational life. First some typical anti-corrosion solutions will be explained. Thereafter, some current research on green alternatives for those anti-corrosion coatings will be analysed. Finally, the end-of-life removal of the coating will be treated.

Types of Anti-Corrosion Treatments

Eventhough different forms of corrosion exist, the most general definition of this phenomenon is as follows: "the destructive attack of a material through interaction with its environment" [70]. The driving mechanism for corrosion is the electrochemical cell, which results in an exchange of electrons between different area's on the material (figure 18.5).

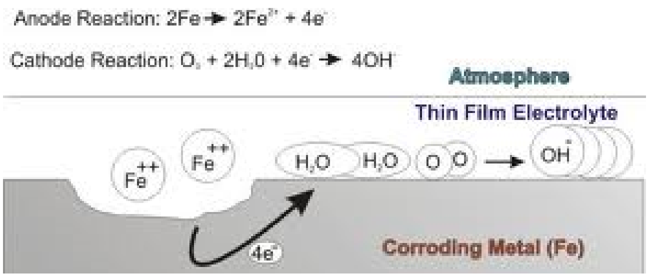

Figure 18.5: Atmospheric corrosion of metals [71]

Different surface treatments exist in order to prevent corrosion of the aircraft structure [72]:

- **Protective coatings:** One way of avoiding corrosion of the aircraft's structure is to protect the corrosion sensitive aluminium from the environment by placing a corrosion insensitive material on top of it. The main drawback of protective coatings is that they do not affect the actual aluminium's surface susceptibility to corrosion. Therefore, protective coating will be used only in aerospace industry in combination with other treatments.
- **Reactive coatings:** Reactive coatings are used to insulate the aluminium in order to suppress the electro-chemical reactions of the material. Chromate is a widely used inhibitor in aerospace anti-corrosion coatings. Therefore different inhibitors have to be applied in order to fit reactive coatings within the Cradle to Cradle® philosophy. This will be analysed in the next paragraph.
- **Anodisation:** Another surface treatment to reduce material corrosion is anodisation. It is a passivation process of the material, which means that it makes the material itself less sensitive to environmental factors such as air and water. Its basic principle is to increase the oxide layer on the aluminium surface, which results in a better corrosion resistance. The main drawback of anodisation is the fact that it reduces the fatigue resistance of the structure. The anodisation process is regarded to be a good, environmental friendly surface treatment. Even though by-products are created, they can be reused for different applications, this will be discussed in more detail in the next section.
- **Biofilm coatings:** Recently, a new anti-corrosion technique has been developed. By using bacterial films, material corrosion can be prevented. Even though the technique would fit perfectly within the Cradle to Cradle® philosophy, those techniques are still in their preliminary development stage and therefore difficult to be implemented already in the highly regulated aerospace industry.

One could see that both protective coatings and biofilm coatings have difficulties to be implemented within the structural design. The first one because of its limited possibilities to safeguard corrosion resistance on itself, the second because of certification issues.

Environmental Friendly Alternatives

The previous part identified a set of possibilities for anti-corrosion coatings. However, one has to be sure about their environmental impact in order to apply them for Cradle to Cradle® aircraft design.
Reactive coatings are widely used within the aerospace industry. Today's used reactive coatings are chromate based. This inhibitor has good corrosion prevention properties, but at the same time the material is both highly toxic and carcinogenic. In order to fit within the Cradle to Cradle® philosophy, alternatives have to be found for chromate. Recently performed research identifies several green alternatives for chromate based coatings [73]. A possible alternative for chrome based coatings is the use of a hybrid Si/Zr/Ce coating. This coating consists of only non-toxic components. Tests have demonstrated the successfulness of this coating on aluminium alloys [74]. Therefore reactive coatings can now be implemented perfectly within the Cradle to Cradle® principle.
Another anti-corrosion treatment identified in the previous section is the anodising process. From itself anodising is environmental friendly as it doesn't consist any heavy metals, halogens or other toxic components. However, two important by-products are created during the anodising process of the aluminium structure: Aluminium hydroxide and aluminium sulfate. Both of them can be reused in several industries as valuable products such as cosmetics, fertilisers. They can even be used in waste-water treatment systems to remove pollutants [75]. Those reintegration possibilities make anodising a well suited anti-corrosion treatment within the Cradle to Cradle® concept.

From the previous paragraphs one can conclude that both types of anti-corrosion treatments could fit well within the Cradle to Cradle® principle. Still, from the previous section one can conclude that reactive coating has easier implementation possibilities within the Cradle to Cradle® aircraft design.

End-of-Life Removal

A final analysis on the anti-corrosion coatings is to look at their applicability within the "design for disassembly" philosophy.

The advantage of anodising the aluminium structure is the fact that no additional material layer is created on top of the aluminium. The additional oxide layer of the aluminium doesn't have to be removed before the aluminium scrap can be remelted and reintegrated within new applications. This is in contrast with reactive coatings, as they form an additional protection layer on top of the aluminium. This makes reactive coatings more difficult for recycling as it requires special removal techniques. Even though eco-friendly coating removal techniques exist, an unavoidable cost increase will be present in the case of reactive coatings. However, anti-corrosion coatings can be applied together with the painting and only one removal of both coatings is required. Therefore reactive coatings will be the most suitable ones for the Cradle to Cradle® aircraft design.

18.3.2 Aircraft Paint

When the aircraft is ready to be delivered, one of the final phases of the production is to paint the aircraft. This painting process not only has to fit within the Cradle to Cradle® philosophy, it also has major influences on the end-of-life treatment of the aircraft.

Today's paintings include the chromate particles required for corrosion protection through the reactive coating method explained before. However, regulations exhibit chromate to be used, as it is an extremely environmentally unfriendly metal. Therefore new solutions need to be researched within paintings. Both heavy metals and low-volatile organic compound (VOC) paint can be created by using water based solutions instead of today's used solvents.

Both Boeing and Airbus are working hard on the development of new, smarter and more environmental friendly painting systems [76] [77]. Reducing the number of layers required and the amount of VOC's are the main drivers for those developments. Most of the environmental effects of aircraft's paintings are due to the corrosion protection. Further research is required to implement the Si/Zr/Ce coating for new aircraft paintings.

Another possibility is the use of paint which reveals material corrosion [78]. This could enhance the maintainability of the aircraft as changes in the paint colour would reveal any corrosion. However, additional and environmental unfriendly chemicals are needed for the revealing of corrosion, which is difficult to be implemented within the Cradle to Cradle® aircraft design.

18.4 Conclusion

Taking into account all mentioned parameters, it can be concluded that the automotive aluminium Al-6022 proves to be a good material for the InfiniCraft. Although its fatigue limit is lower and it has reduced fracture toughness, the alloy is lightweight, cost effective and has a good corrosion resistance. Designing the InfiniCraft for a shorter lifetime will compensate for the reduced mechanical properties. Combined with its excellent recycling capabilities (it can be recycled into the automotive sector), this material is perfectly able to meet the Cradle to Cradle® requirements and structural requirements. However, in order to really understand the material behaviour, and certify it for aerospace purposes, it is essential to perform further analysis on fatigue behaviour and crack propagation.

For the anti-corrosion treatment of Al-6022 two different possibilities where identified: reactive coating and anodising. Reactive coating has been selected as anodising would imply additional fatigue issues. Recent research proves that those coatings can fit perfectly within the Cradle to Cradle® principle and will be available by 2025. For the painting itself the most important issue is the change from solvent based solution to water based solutions, which would reduce the environmental impact of today's coatings. Extensive research has to be performed on this topic as stability and performance of the paint is reduced drastically when reducing the solvents in the paint.

Chapter 19 | Primary Structures

Another important aspect of the structural design of the InfiniCraft is the structure type. In this chapter different structure types are discussed, concluding with a final design choice regarding the aircraft structure.

19.1 Design Options

Here, a description is given on the main design options for the aircraft primary structure. This section is generally based on the Pilot's Handbook written by the U.S. Department of Transportation [79].

19.1.1 Truss Structure

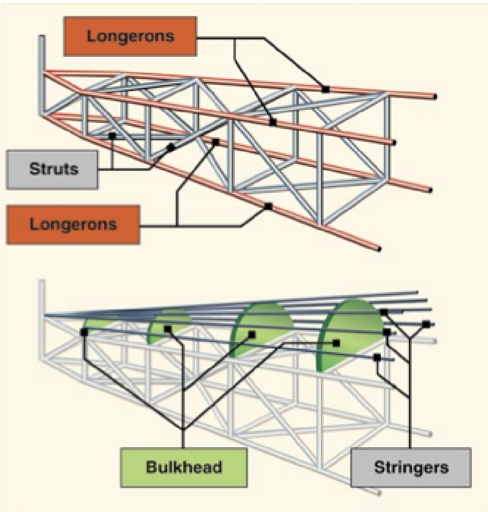

Figure 19.1: Truss-type fuselage structure [79]

Nowadays, agricultural aircraft utilise open trusses as the primary structure for the fuselage design. A truss-type fuselage is constructed of steel or aluminium tubing. The result is a strong and reliable structure. In order to streamline the aircraft and improve the performance, the truss members may be enclosed with a light-weight material.
Two types of truss structures are used in the aerospace industry: the Pratt truss and Warren truss. The first one was used in the early days of the aerospace industry and was really difficult to streamline. The second one has a better streamline, is capable to carry both tension and compression loads and has a better strength. A graphical representation of a truss structure is displayed in figure 19.1.
The prior disadvantage of this type of structure is the shape which causes higher drag compared with semi-monocoque structures. This is due to the fact that the truss structure has an angular shape.

19.1.2 Semi-Monocoque

The most popular type of structure that is used in aircraft designs is the semi-monocoque structure, which is displayed in figure 19.2. This structure type is based on a long tube reinforced with a large number of structural elements. The longerons carry most of the bending loads, whereas the stringers serve as fill-ins. Stringers do have some rigidity, however they are most of the time only used to shape and attach the skin. The heavy longerons hold the bulkheads and formers, whereas the bulkheads and formers hold the stringers. Next to these longitudinal reinforcements, also circumferential elements need to be used. These vertical members are the bulkheads, frames and formers. The reinforcements are not the only structural components in a semi-monocoque structure. Part of the load is carried by the skin. The thickness of the skin can be varied according to the stress at a particular location [80] [81].

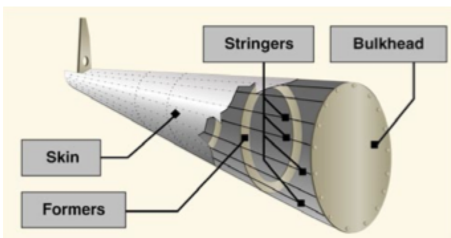

Figure 19.2: Semimonocoque structure [79]

19.1.3 Monocoque

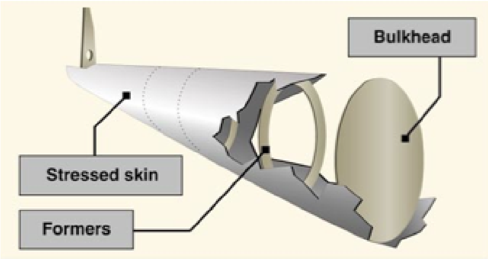

Figure 19.3: Monocoque empennage [79]

This aircraft structure makes use of a stressed skin which carries almost all loads. For this reason there is no need for internal bracing. This will save weight and maximize the space inside the aircraft. Figure 19.3 shows an example of a monocoque aircraft empennage. A major drawback of this structure is however the complexity of the design. The monocoque structure needs to be strong enough to keep its shape, which may lead to complex joints between the skin panels when using aluminium.

19.2 Design Option Discussion

After assessing the different structure types, the advantages and disadvantages can be found in table 19.1.

Table 19.1: Advantages and disadvantages for the three structure types

Structure type	Advantages	Disadvantages
Truss structure	+ Easy recyclability + Ease of manufacturing + Robust structure + Ease of maintenance	- Lack of aerodynamic shape - Heavy structure
Semi-monocoque structure	+ Weight reduction due to load carrying skin + Aerodynnamic shape + Widely used structure	- Difficulties in maintenance - Less robust structure
Monocoque structure	+ Major weight reduction + Aerodynamic structure	- Difficulties in maintenance - Replacability more difficult

19.3 Conclusion

When taking into account the requirements set for the Cradle to Cradle® design, two structure types provide a good solution for the design: the truss structure and the semi-monocoque structure. Compared to a monocoque structure, the other two possibilities are easier to maintain and provide better recycling opportunities when properly applied. Truss structures are however heavier than semi-monocoque structures. When considering the operational costs, lightweight structures are more cost- effective. Finally, when considering the fact that the design is supposed to provide an example to others, it can be concluded that the semi-monocoque structure is the best solution for the design, as most current aircraft use this structure type. Maintenance issues should however be addressed, as they contribute to the operating costs of the aircraft.

Chapter 20 | Stress Analysis

Now that the material and the type of the primary structure are chosen to be aluminium and semi-monocoque, the wing and fuselage structures can be sized. To do so, a preliminary analysis on the stress distributions is performed. In the first section, the maximum and minimum load factors will be computed. In the second section, the used assumptions are stated, whereafter the governing equations will be introduced. In the fourth section, the wing box is analysed. Next, in the fifth section the stresses in the fuselage are computed. Finally a preliminary flutter analysis is performed on the aircraft.

20.1 Loading Diagrams

In this subsection, the generation of the V-n diagram will be discussed. From this diagram, the maximum and minimum load factor, n_{max} and n_{min}, can be determined. In order to produce the diagram, the load factors during manoeuvres and gusts encounters must be evaluated. The highest and lowest values determine the limit load factors. Finally, the determined values are multiplied with a standard safety factor of 1.5 to determine the ultimate load factor.

20.1.1 Manoeuvre Loading Diagram

The loading during manoeuvres are specified in the Airworthiness Certification (CS-23) [10]. Since the InfiniCraft will be a trainer aircraft, it will be certified as a utility aircraft which can do basic acrobatic manoeuvres including spin recovery and stall conditions. From this requirement it follows that the maximum load factor will be 4.4. The minimum load factor during manoeuvres for utility aircraft is equal to -0.4 times the maximum load factor [82].

$$n_{max} = 4.4 \quad \text{and} \quad n_{min} = -1.76$$

The first curve of the manoeuvre load diagram, displayed as the solid contour in figure 20.1, represents the maximum achievable positive lift at the specified flight speeds. This line runs from point 0 to point A_{clean} and is defined by equation 20.1.

$$n = \frac{C_{L_{max}} {}^1\!/\!{}_2\, \rho V^2 S}{W} \tag{20.1}$$

The line from the origin to point A_{land} also uses equation 20.1, but incorporates the C_L value during landing conditions. At point A_{clean}, the manoeuvre speed is $V_a = 58.4\ m/s$. This is the speed at which the largest angle of attack and the highest load factor are obtained. From point A_{clean} to point D the load factor is the maximum load factor n_{max}. At point D, the dive speed is found. This speed is defined as 1.5 times the cruise speed [83]. Since the cruise speed is 200 km/h, the dive speed equals:

$$V_d = 1.5 \cdot V_c = 1.5 \cdot 200\,\frac{km}{h} = 1.5 \cdot 55.6\,\frac{m}{s} = 83.3\,\frac{m}{s}$$

From point E to point F, the load factor varies linearly from zero to n_{min}. Point E is situated at the dive speed, whereas point F corresponds to the cruise speed V_c. From point F to point H the load factor stays constant at a value of n_{min}. The part from point H to the origin is the negative of equation 20.1. Point H corresponds to an airspeed of $V_h = 36.9\ m/s$.

20.1.2 Gust Loading Diagram

The gust loading diagram shows the load factor as a result of gusts. Gusts need to be evaluated at three speeds: a gust of $\hat{u} = 66\ ft/s$ at speed V_b, a gust of $\hat{u} = 50\ ft/s$ at speed V_c and a gust of $\hat{u} = 25\ ft/s$ at speed V_d [82]. These speeds are obtained in ft/s from statistics but should be used in SI units in the following equations. V_c and V_d are already defined but V_b is new. This speed lies between the stall speed in clean configuration $V_{s_{clean}}$ and the cruise speed V_c. More specifically, V_b should be 43 knots lower than V_c [83]. It follows that:

$$V_b = V_c - 22.1\,\frac{m}{s} = 33.4\,\frac{m}{s}$$

The load factors are calculated with equation 20.2.

$$n = 1 \pm \frac{1/2\,\rho V C_{L_\alpha} K \hat{u} S}{W} \tag{20.2}$$

In this equation, K represents a correction factor to include the effects of the size of the aircraft in the gust response. It is given by equation 20.3 [83]. $\hat{u}$ represents the gust speeds as mentioned above. C_{L_α} is the slope of the $C_L - \alpha$ curve of the aircraft.

$$K = \frac{0.88\mu}{5.3 + \mu} \quad \text{where} \quad \mu = \frac{2W}{\rho g \bar{c} C_{L_\alpha} S} \tag{20.3}$$

The obtained gust load factors from these equations can be found in table 20.1. The gust load diagram is shown in figure 20.1 as the dashed contour.

Table 20.1: Gust load factors

Speed	Positive load factor	Negative load factor
$V_b = 33.4\ m/s$	3.50	-1.50
$V_c = 55.6\ m/s$	4.14	-2.14
$V_d = 83.3\ m/s$	3.36	-1.36

20.1.3 Combined Loading Diagram

Figure 20.1 is obtained by combining the manoeuvre and gust loading diagrams.

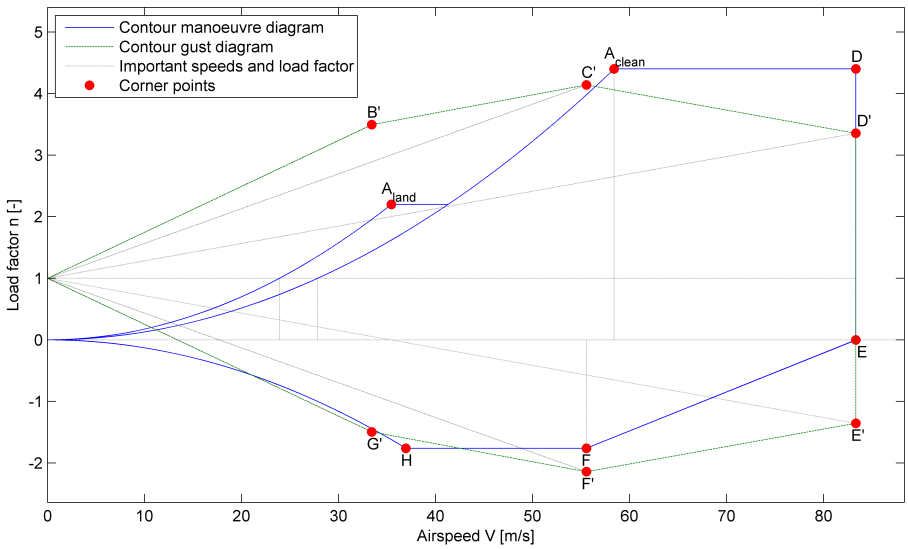

Figure 20.1: combined load diagram

As can be seen in figure 20.1, the maximum load factor is determined by the manoeuvre loads, while the minimum load factor is determined by the gust loads. From these numbers the ultimate load factors can be computed.

$$n_{max} = 4.4 \qquad n_{ult_{max}} = n_{max} \cdot 1.5 = 6.6$$

$$n_{min} = -2.14 \qquad n_{ult_{min}} = n_{min} \cdot 1.5 = -3.21$$

20.2 Design Choices and Assumptions

After determining the load factors for which the design should be sized, a preliminary sizing can be performed on the wingbox structure and the fuselage. Before starting with this analysis however, a number of assumptions and preliminary design choices have to be made in order to simplify and build the models. This section will describe these assumptions and design choices.

20.2.1 Design Choices

- The wing is straight with no taper.

- The wing has no sweep.
- A strut is used to relieve the bending stress on the wing structure.
- The wing box width is assumed to be half of the local chord length.
- The front spar lies on the quarter chord length of the wing.
- A semi-monocoque structure is used for both the wing and fuselage structure.

20.2.2 Assumptions

Below, the assumptions made are stated together with their effect on the analysis.

Cut-outs For both the wing box and the fuselage analysis, cut-outs are neglected. This results in an idealised structure which has no local stress concentrations. In the real case however, these cut-outs are present and would introduce local stresses in the structure.

Wing Box The following assumptions have been made regarding the wing box structural analysis:

- The lift is assumed to be acting at the quarter chord point and hence on the front spar of the wing box. The effect of this assumptions is that the lift is introduced as a point force and hence locally introduces higher stresses in the structure.
- The average of a rectangular and an elliptical lift distribution is assumed to be acting on the wing. This has as effect that the distribution is more accurate than a simple rectangular one, but still not the same as the real lift force distribution.
- Drag forces are neglected in the analysis since they are very low compared to the lift force. By doing so, the torque and hence the shear stresses from the drag are neglected and the loads on the wing are underestimated.
- The distributed wing weight is assumed to be constant along the wing span. The effect of fuel tanks on the local wing weight is neglected. This results in less bending relief at the root and yields a small overdesign.

Fuselage The following assumptions have been made regarding the fuselage structural analysis:

- As only loads in the vertical direction are analysed, drag and thrust forces are neglected. Due to this assumptions, the loads on the fuselage are underestimated.
- The fuselage interior and structure are assumed to be a distributed force acting along the fuselage length. This resembles the most to the real situation and delivers a more realistic simulation.

20.3 Governing Equations

This section discusses the governing equations to perform the stress analysis. The equations are based on the book "Aircraft Structures for Engineering Students", written by Megson [84].

Shear Force

The first step in the calculation of the stresses in the structure is the determination of the shear force. This can be done by taking into account all the forces and distributed loads that act on the structure. For the wing, the main force is the lift and the wing weight, while for the fuselage a more complicated loading pattern needs to be considered. The detailed shear force equations will be given in the wing and fuselage sections. In equation 20.4, a generalised equation is shown.

$$V_i = V_{i-1} + W_{XX_i} + q_{xx} \cdot (y_i - y_{i-1}) \tag{20.4}$$

Bending Moment

Integrating the shear force distribution results in the moment distribution. This calculation is done using the trapezoidal integration method, defined by equation 20.5. In this equation, the y-direction is introduced. The full reference frames are explained in sections 20.4.1 and 20.5.1.

$$M_i = M_{i-1} + \frac{V_{i-1} + V_i}{2} \cdot (y_i - y_{i-1}) \tag{20.5}$$

Centroid

The vertical centroid coordinate is calculated with equation 20.6. In this equation z is the vertical distance from the reference frame to the respective center of gravity of each element.

$$z_{c_i} = \frac{\sum_{m=1}^{n} z_m \cdot A_m}{\sum_{m=1}^{n} A_m} \tag{20.6}$$

Second Moment of Inertia

The area moment of inertia is calculated with equation 20.7. Taking into account the respective assumptions regarding the horizontal shear forces and taking into account symmetry, only the area moment of inertia around the horizontal axis is calculated. Applying the thin-walled theory to the structures yield for the wing box case:

$$I_{xx_i} = \sum_{m=1}^{n} \left(I_{xx_m} + (z_m - z_{c_i})^2 \cdot A_m \right) \tag{20.7}$$

Bending Stress
After simplification of the bending stress equation, the bending stress distribution can be calculated with equation 20.8. With the results of this equation, the spanwise bending stress distribution can be determined at every point on the wing box and the fuselage.

$$\sigma_{z_i} = \frac{M_i}{I_{xx_i}} \cdot z \tag{20.8}$$

Shear Stress
Finally, the shear stress is determined for both the wing box and fuselage cross section. Here the procedures to obtain these results are explained. The shear flow acting on each skin panel can be calculated with the simplified shear flow equation 20.9. The simplifications are valid due to the assumptions that the wing/fuselage is symmetrical and no horizontal shear force acts on the structure.

$$q_{s_k} = -q_{b_k} + q_{s_0} \tag{20.9}$$

Before computing these values, the constant shear flow $q_{s,0}$ has to be determined.
First, a cut is made in the left bottom corner. This changes the situation to an open-section problem with no constant shear flow. At the cut, the shear flow is zero. The shear flow in each of the panels is then equal to:

$$q_{b_k} = -\frac{S_z}{I_{xx}} \int_0^{s_i} t_k z_k \, ds + q_{b_{k-1}} \tag{20.10}$$

Hereafter the cut is closed and the moments resulting from the open section shear flows are taken around the bottom right corner for simplicity, as this is the point where the line of action of the lift crosses. The total moment equation is then set equal to zero, resulting in equation 20.11.

$$\sum M = \oint q_b p ds + 2Aq_{s,0} \tag{20.11}$$

With this equation, $q_{s,0}$ can be determined, whereafter the values can be implemented in equation 20.9.
Finally, the shear stress can be computed using equation 20.12.

$$\tau = \frac{q_s}{t_{skin}} \tag{20.12}$$

Von Mises Yield Criterion
The Von Mises stress equation is given by equation 20.13.

$$\sigma_Y = \frac{1}{\sqrt{2}} \sqrt{(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6\left(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2\right)} \tag{20.13}$$

Following from the assumptions stated in section 20.2, it is possible to eliminate some terms. This leads to equation 20.14.

$$\sigma_Y = \sqrt{\sigma^2 + 3\tau^2} \tag{20.14}$$

Buckling Load Criteria
As a final check the buckling load criteria should be addressed in order to prevent buckling to occur. The buckling load criteria is defined by equation 20.15.

$$F_{Cr} = \frac{E_i I_{xx} \pi^2}{L^2} \tag{20.15}$$

20.4 Wing Box Analysis

In this section the stresses in the wing box will be analysed. First, the reference frame is introduced after which the two main load cases for the wing box will be described and the stresses are calculated.

20.4.1 Reference Frame

For the stress analysis of the wing box, two reference frames are used. One reference frame with the origin at the wing root and one reference frame with the origin at the center of gravity of the wing box. These two reference frames are displayed in figure 20.2.

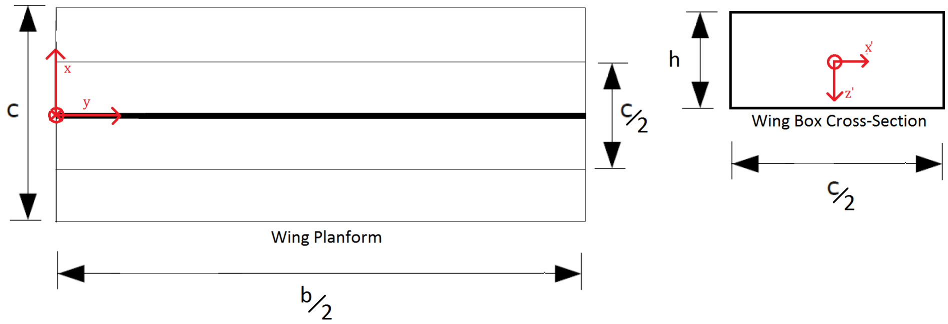

Figure 20.2: Wing box reference frames

20.4.2 Wing Box Load Case: Lift

From the load cases described in section 20.1, two load factors were determined to be critical for the wing box: the +6.6 g and the -3.21 g load cases. Here, the -3.21 g load case represents a negative lift distribution, where the lift force is pointing downwards.

These load factors are introduced to the wing box model by multiplying the elliptical lift distribution with each of the respective load factor, assuming cruise conditions.
The distributed lift force has been obtained using the lifting-line theory, as described in [85]. The average lift distribution is obtained by taking the average of the optimum elliptical distribution, obtained from equation 20.16, and the constant distribution, acquired from equation 20.17.

$$L_{elliptical}(y) = \rho V \Gamma_0 \sqrt{1 - \left(\frac{2y}{b}\right)^2} \tag{20.16}$$

$$L_{rectangular}(y) = \frac{nW}{b} \tag{20.17}$$

In equation 20.16, Γ_0 is defined by equation 20.18.

$$\Gamma_0 = \frac{4nW}{\pi \rho V b} \tag{20.18}$$

With this method, a representation of the lift distribution is obtained. Below, in figures 20.3 and 20.4 the lift distribution is shown for both the +6.6 g and -3.21 g load case respectively. Note that the axes are inverted to indicate the actual direction of the lift force. For example, for the +6.6 g load case, the lift force is directed upwards. However, the positive z axis, as displayed in figure 20.2, is pointing downwards.

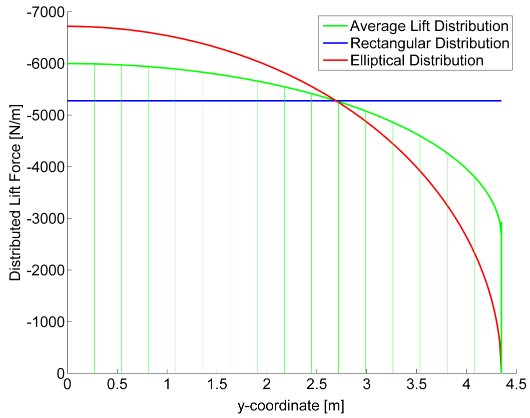

Figure 20.3: Lift distribution +6.6 g

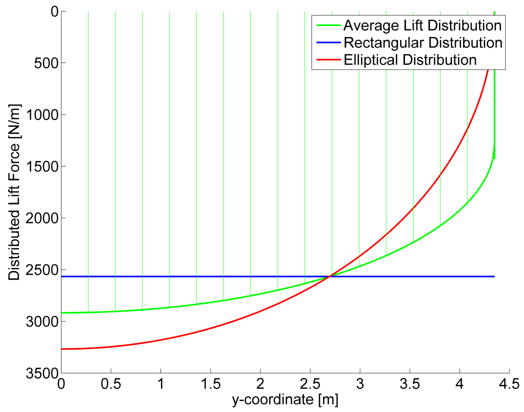

Figure 20.4: Lift distribution -3.21 g

20.4.3 Wing Box Design Parameters

After several iterations, an optimal design for the wingbox was acquired. Below, in table 20.2, the final design parameters are given. On this design the final stress analysis was performed. It should be noted that the spar thickness is equal to the sheet thickness in order to simplify the model.

Table 20.2: Wingbox design parameters

Symbol	Value
t_{sheet}	$2\ [m]$
$A_{stringers}$	$2.3\ \left[cm^2\right]$
n_{top}	5
n_{bottom}	4
I_{xx}	$1.15 \cdot 10^7\ \left[mm^4\right]$

20.4.4 Force and Moment Diagrams

After determining the lift distribution along the wing, an analysis can be performed for the shear force and moment distribution.

Shear Force Distribution

Using equation 20.4, the shear force distribution along the wing box was determined, taking into account the distributed wing weight force. The results for both load cases are shown below in figures 20.5 and 20.6. It can be noticed that for the +6.6 g load case, the strut is pulling the wing downward wile in the -3.21 g load case, the strut pushes the wing upward. For both load cases, a different strut force is used to optimise the design. Later in this section, a more detailed analysis on the strut design will be given. Again, the axes are inverted.

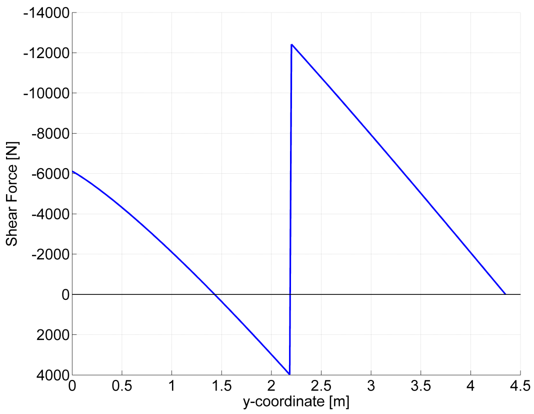

Figure 20.5: Shear force diagram +6.6 g

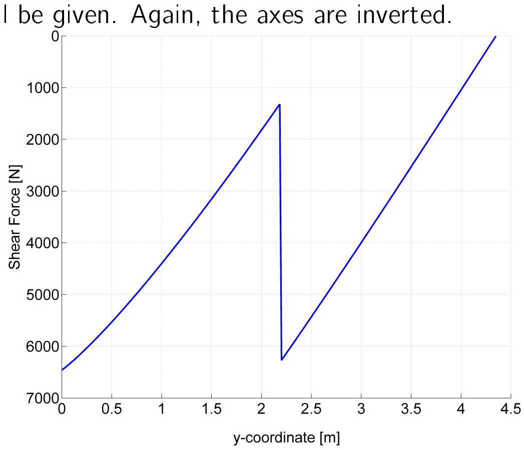

Figure 20.6: Shear force diagram -3.21 g

Moment Distribution

By integrating the shear force distribution with equation 20.5, the moment distribution along the wing box is obtained. The results are plotted in figures 20.7 and 20.8.

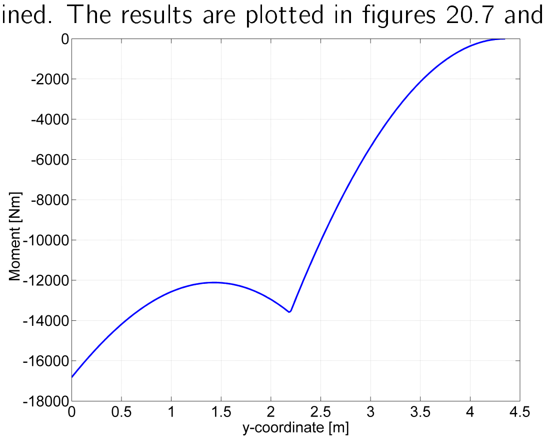

Figure 20.7: Bending moment diagram +6.6 g

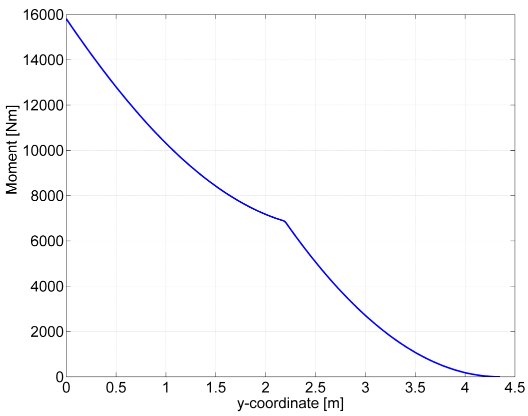

Figure 20.8: Bending moment diagram -3.21 g

Numerical Results

Table 20.3 shows the numerical results for the resultant shear force and moment at the root of the wing box.

Table 20.3: Root shear force and bending moment

Symbol	Definition	+6.6 g	-3.21 g
V	Shear force [N]	6100	6500
M	Bending moment [Nm]	16800	15800

20.4.5 Stress Analysis

Finally, having determined the shear force and moment distribution along the wing box, an analysis can be done on the stress distribution. First, the bending stresses and shear stresses are calculated after which the Von Mises stress distribution is determined. The latter represents the yield criteria of the wing box and can be compared to the design strength of the Al-6022 alloy, determined to be 126 MPa in section 18.2.

Bending Stress

The bending stress distribution is calculated using equation 20.8. The results are shown below in figures 20.9 and 20.10. The location of the strut can clearly be seen at the stress concentration at 2.2 meters from the root. It should be noted that in the figures, the right side of the figure is the front of the wing box and the spanwise values start at the tip of the wing box. The values for the bending stress are given in [MPa].

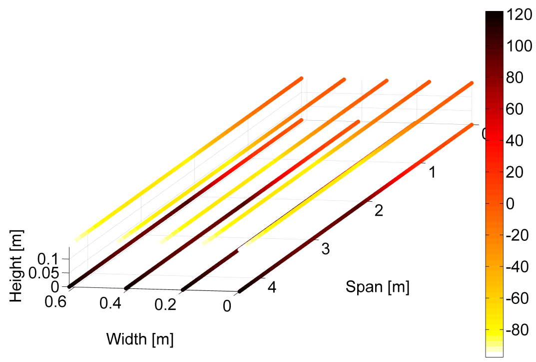

Figure 20.9: Bending stress distribution +6.6 g

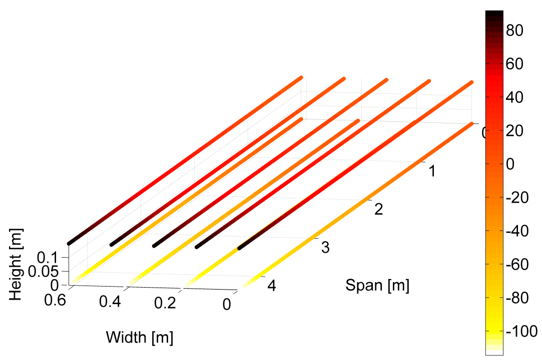

Figure 20.10: Bending stress distribution -3.21 g

Shear Stress

Using the method described in section 20.3, the shear stress along the wing box is calculated. In figures 20.11 and 20.12 below, the booms represent the shear flow in the skin which surrounds the respective booms. The values for the shear stress are given in [MPa]

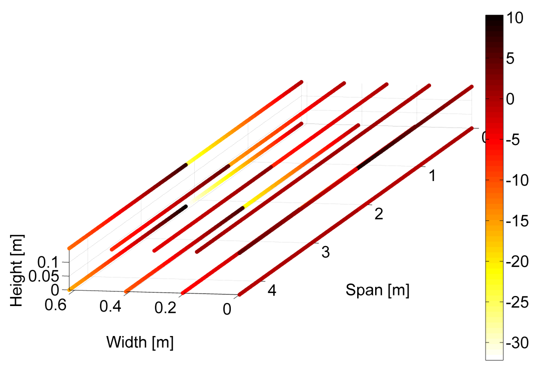

Figure 20.11: Shear stress distribution +6.6 g

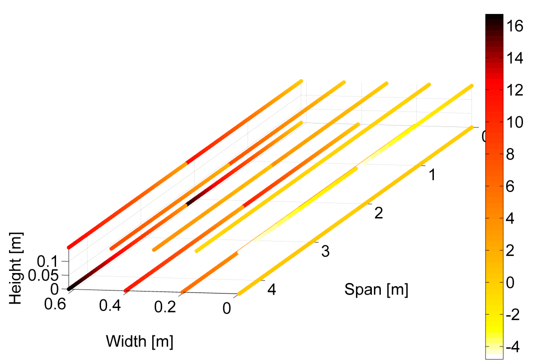

Figure 20.12: Shear stress distribution -3.21 g

Von Mises Stress

Finally, the yield criterion, or the Von Mises stress, is computed. The results for both load cases are displayed for both load cases in figure 20.13 and figure 20.14 in [MPa].

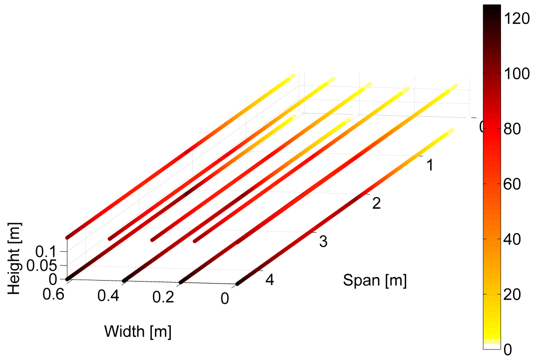

Figure 20.13: Von Mises stress distribution +6.6 g

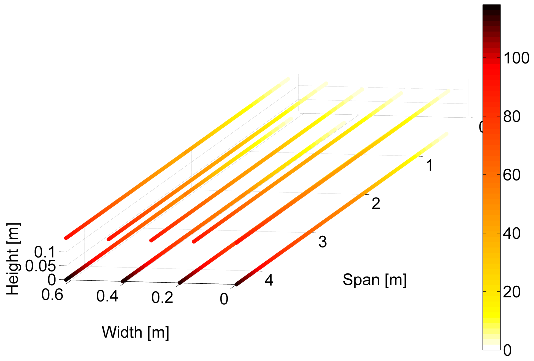

Figure 20.14: Von Mises stress distribution -3.21 g

Numerical Results

In table 20.4, the maximum stress levels are displayed for both load cases.

Table 20.4: Maximum stress levels

Symbol	+6.6 g	-3.21 g
$\sigma\,[MPa]$	121.9	91.7
$\tau\,[MPa]$	10.3	16.7
$\sigma_Y\,[MPa]$	124.9	118.2

20.4.6 Strut Analysis

The final design feature that needs to be analysed is the strut. Using equation 20.15, the strut is designed to withstand the buckling load criteria. As the -3.21 g load case is the maximum load case where the strut is in compression, this will be the load case for which the strut is designed. In table 20.5, the strut parameters are displayed. The strut weight is based on the fact that the strut is made from the same material as the skin.

Table 20.5: Strut design parameters

Symbol	Value
F_{Strut}	5000 $[N]$
L_{Strut}	2.5 $[m]$
d_{Strut}	5.18 $[m]$
t_{Strut}	1.8 $[mm]$
m_{Strut}	1 $[kg]$

20.4.7 Weight Calculation

As a final check, the total wing structural weight is compared to the class II wing weight estimation, described in section 9.2. The wing weight structure is calculated by adding the wing box structural weight to the strut weight. The wing box structural weight is calculated with equation 20.19:

$$W_{structure} = \rho_{Al-6022}\, A_{structure}\, Lwingbox \tag{20.19}$$

In table 20.6, the results are shown.

Table 20.6: Weight comparison

Symbol	Stress Analysis	Class II Estimate
$W_{Structure}$	86	63

It can be seen that the weight computation from the stress analysis is higher than the estimated weight. This can be explained by the fact that the analysis was performed with a low fidelity tool. Also, the class II weight estimation does not take into account the use of the 6022 alloy. It can be concluded that the use of the 6022 alloy is feasible for this design, although it does require extensive future testing and optimisation.

20.5 Fuselage Analysis

In this section the stresses in the fuselage will be analysed. First, the reference frames will be introduced. After this, the load cases on the fuselage will be explained and finally the stresses will be calculated.

20.5.1 Reference Frame

For the stress analysis of the fuselage, two reference frames are used. One reference frame with the origin at the aircraft nose and one reference frame with the origin at the center of the local fuselage cross section. The two reference frames are displayed in figure 20.15.

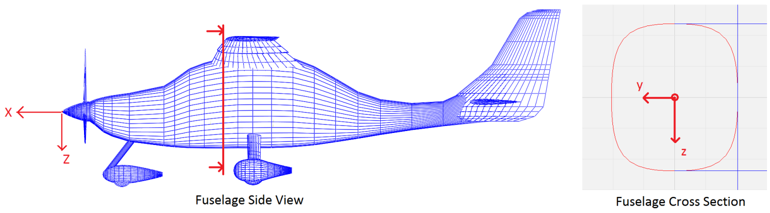

Figure 20.15: Fuselage reference frames

20.5.2 Fuselage Load Case

For the design of the fuselage structure, two load cases have been identified: flight under maximum and minimum load factors. First, all forces acting on the fuselage have to be identified. These forces can be seen in figure 20.16. During the analysis of the fuselage, all forces will be multiplied with the load factor obtained in section 20.1.

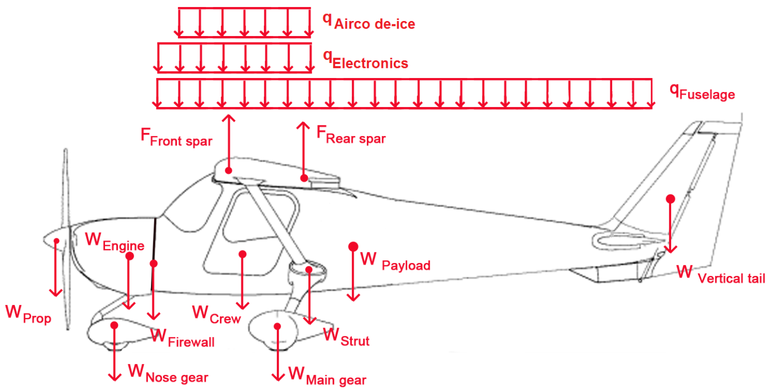

Figure 20.16: Fuselage load case

Three main categories can be seen:

1. **Aerodynamic forces (F):** The main aerodynamic force acting on the fuselage is the lift force generated by the main wing. In the analysis, the lift is assumed to be distributed from the front to the rear spar. Drag is neglected in the stress analysis.
2. **Point gravity forces (W):** This category of forces are induced by distinct components or loads on the aircraft. These components are: the propeller, the engine, the nose and main landing gear, the two passengers, the payload, the vertical and horizontal tail. Weights and locations for these components can be found in tables 10.1 and 10.2 on page 22. The weights are obtained from the class II weight estimation, while the locations are determined from reference aircraft and estimations.
3. **Distributed gravity forces (q):** These forces are distributed over the fuselage and are introduced by the electronics and wiring (from the fire wall till the rear spar), furnishing and the fuselage weight (from the fire plate to the end of the fuselage). The (total) weights of the components can be found in table 10.1. The locations were again taken from reference aircraft or estimated.

Next to the forces in the vertical plane, also a torque is exerted on the aircraft fuselage structure. It is introduced by the vertical tailplane. The torque is calculated with equation 20.20.

$$T = Z_{tail} \cdot \left(C_{L_{tail}} {}^{1}\!/_{2} \rho V^2 S\right) \tag{20.20}$$

InfiniCraft

In this equation, Z_{tail} is the distance from the center of the fuselage section to the resultant vertical lift vector ($1\,m$). $C_{L_{tail}}$ is estimated to be 1. V is defined as the speed the aircraft should never exceed and is equal to 1.2 times the dive speed. S is the area of the vertical tail and is estimated to be $1.8\,m$.
The model in figure 20.15 was modelled in a program called OpenVSP [86]. From this program, the width and the height of each section was obtained, as shown in figure 20.17.

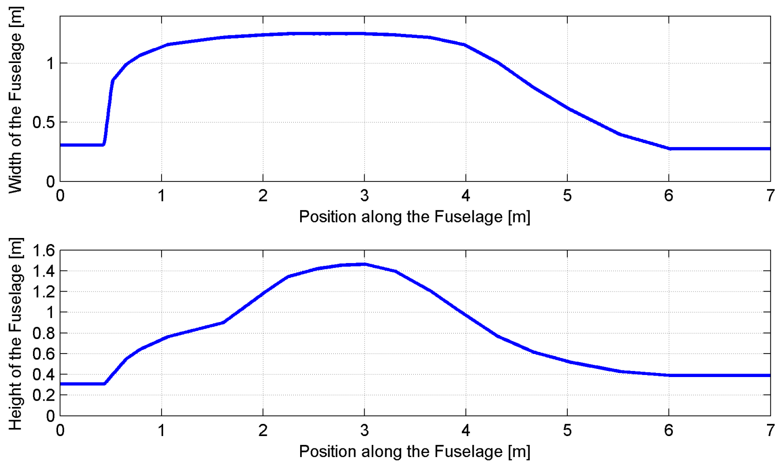

Figure 20.17: Fuselage width and height

The fuselage weight was distributed according to the size of the cross section. This means that more weight was put at the cabin and less weight at the tail of the aircraft.
The stress calculations will be done for the $6.6g$ load case since this introduces the highest loads on the fuselage. In the end, also the $-3.21g$ load case will be considered to guarantee the structure can also handle this case.

20.5.3 Force and Moment Diagrams

Using equation 20.4, the shear force distribution on the fuselage was determined. The result can be seen in figure 20.18. Note that the y-axis is inverted. This was done to present the force in a comprehensive way as the reference frame is positive downwards. Since the aircraft is in equilibrium, the shear force at the front and back of the aircraft are both zero. The maximum and minimum shear force are respectively $12\,574\,N$ and $-7\,843\,N$.

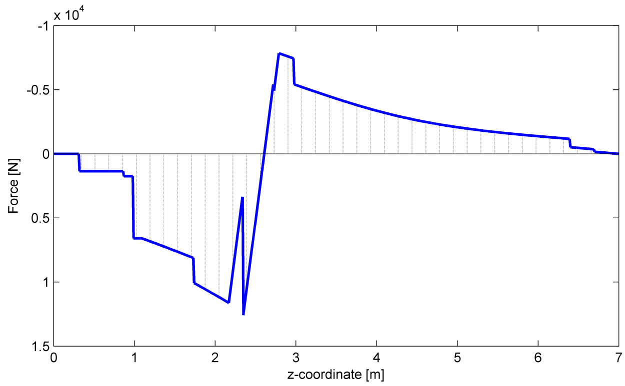

Figure 20.18: Shear force acting on the fuselage

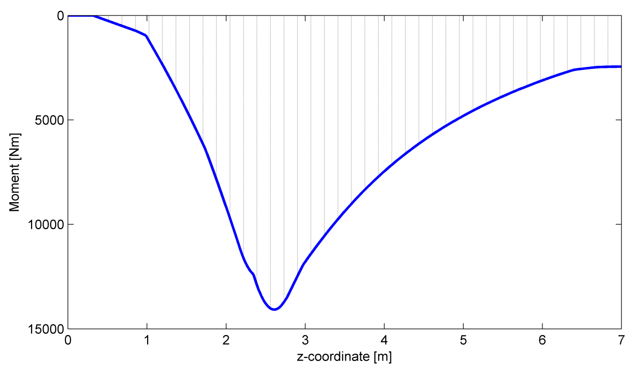

Figure 20.19: Bending moment acting on the fuselage

When the shear force distribution is integrated using equation 20.5, the moment distribution along the fuselage is obtained. This result can be seen in figure 20.19. The maximum bending moment is $14\,077\,Nm$.

20.5.4 Stress Analysis

Now that the loads on the fuselage structure are determined, the stresses can be calculated. In chapter 18 it was calculated that the fatigue limit of Al-6022 is equal to $108\,MPa$. Therefore, the lifetime of the fuselage can be around 30 years.

Bending Stress

The bending stresses are absorbed by the stringers that run in the length-wise direction of the fuselage. After some iteration, four stringers on the top side and four stringers on the bottom side with an area of 0.5 cm^2 each are selected. The stresses in the top and bottom stiffeners can be seen in figure 20.20.

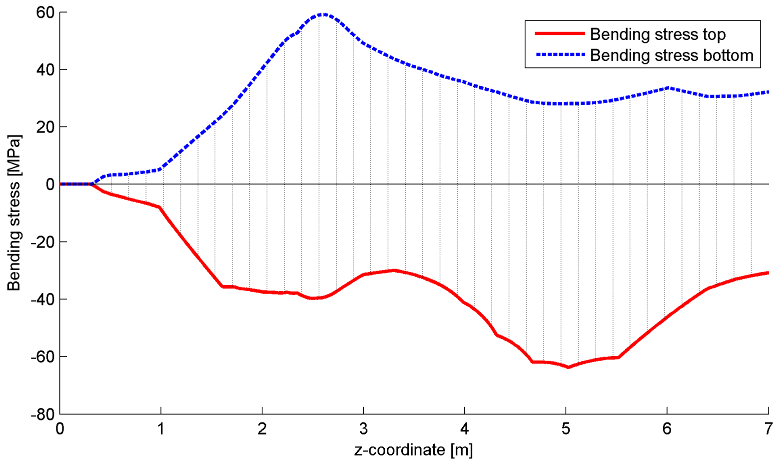

Figure 20.20: Bending stress at the top and bottom of the fuselage

The maximum stress in the stiffener material is 63.7 MPa, which is well below the fatigue limit of 108 MPa. However, as the stiffeners are already small, making them even smaller would introduce problems during the manufacturing. It should be noted that the maximum yield stress will be calculated with the Von Mises criterion, which will be done later in this section, after the calculations of the shear stresses.

Shear Stress

The shear stress is absorbed by the skin. As mentioned before, the shear flow distribution consists of a component due to the shear force and a component due to the torque of the vertical tail plane. After some iterations, a skin thickness of 1 mm was obtained. The output of the calculations can be seen in figure 20.21.

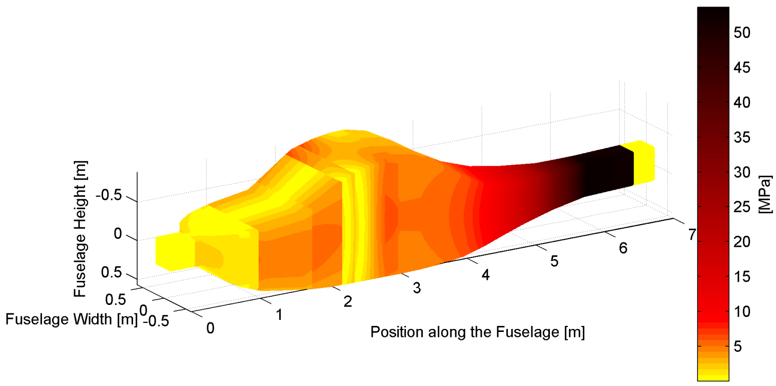

Figure 20.21: Shear stress in the fuselage structure

The maximum shear stress is 53.6 MPa which is located at the end of the fuselage. There are two reasons for this: first of all it is where the torque of the vertical tail plane is introduced in the structure. Secondly, the structure is very narrow at that point. The resistance against torque is therefore lower and larger stresses are observed.

Von Mises Stress

The Von Mises stresses are calculated using equation 20.14. They combine the bending and shear stress distribution to compare it with the strength of the selected material. In case of the InfiniCraft, the Von Mises stress should not exceed 108 MPa. The stress distribution is shown in figure 20.22. The maximum Von Mises stress in the structure equals 102.6 MPa, which is just under the fatigue limit of 108 MPa, as the fuselage will be designed to last much longer than the wing box, around 30 years.

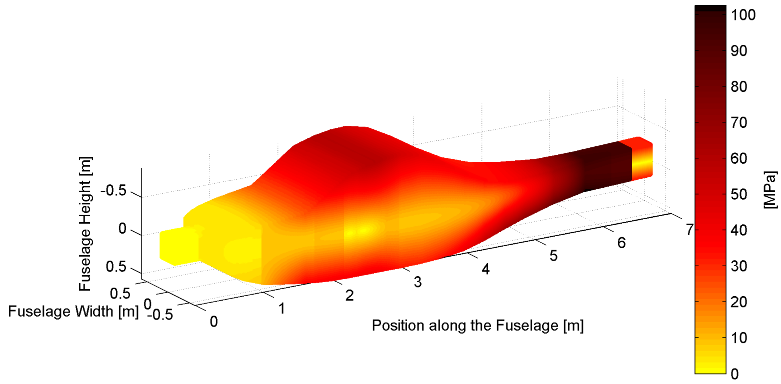

Figure 20.22: Von Mises stress in the fuselage structure for 6.6 g load case

The whole process can also be done using the most negative load factor of −3.21. The results of these calculations are shown in figure 20.23.

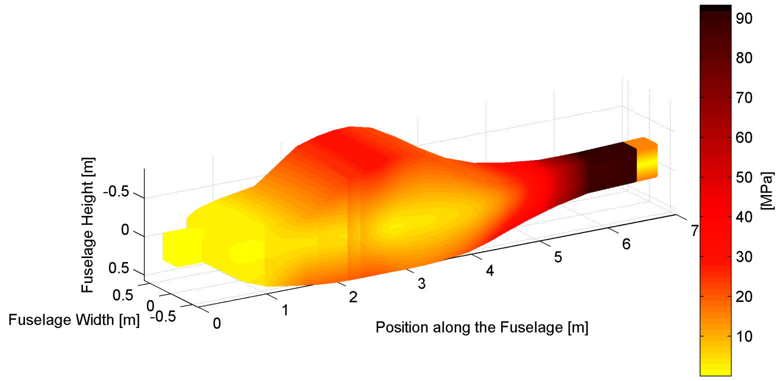

Figure 20.23: Von Mises stress in the fuselage structure for −3.21 g load case

20.5.5 Weight Calculation

Now that the fuselage is designed, a weight estimation can be performed. Three components need to be considered when calculating the weight: the stiffener weight, the skin weight and the circumferential stringer weight.

Since the density of aluminium is 2700 $^{kg}/_{m^3}$ [87], the stiffener weight can be calculated as follows:

$$\begin{aligned} m_{stiff} &= l_{fuselage} \cdot nr_{stiff} \cdot A_{stiff} \cdot \rho_{al} \\ &= 7\,m \cdot 8 \cdot 0.5 \cdot 10^{-4}\,m^2 \cdot 2700 ^{kg}/_{m^3} \\ &= 7.6\,kg \end{aligned}$$

The skin weight can be calculated by computing the volume of the skin for every section, summing it up and multiplying it with the density of aluminium. In the following equation w_k and h_k indicate the width and height of section k. t_{skin} is the skin thickness.

$$\begin{aligned} m_{skin} &= \sum_{k=1}^{N} \left(2\left(w_k + h_k\right) t_{skin} \left(x_k - x_{k-1}\right)\right) \rho_{al} \\ &= 0.02297 m^3 \cdot 2700 \frac{kg}{m^3} \\ &= 62.0\,kg \end{aligned}$$

Another component of the fuselage are the circumferential formers. It is estimated that there is one every 0.5 m. The area A_{circ} of each stringer is assumed to be 1 cm^2. The mass can be computed with:

$$\begin{aligned} m_{circ} &= \sum_{k=1}^{15} \left(A_{circ}^2 \left(width_k + height_k\right)\right) \rho_{al} \\ &= 0.00471 m^3 \cdot 2700 ^{kg}/_{m^3} \\ &= 12.7\,kg \end{aligned}$$

Adding the components, the fuselage mass is computed to be:

$$\begin{aligned} m_{fuselage} &= m_{stiff} + m_{skin} + m_{circ} \\ &= 7.6\,kg + 62.0\,kg + 12.7\,kg \\ &= 82.3\,kg \end{aligned}$$

Although this is below the estimated fuselage weight of 104 kg from the class II weight estimation, it needs to be stated that the fuselage weight computation in this chapter does not contain any special reinforcements, the fire plate nor interior attachments. Still, it proves that it is possible to build the InfiniCraft using automotive aluminium.

20.6 Flutter Analysis

A final important phenomenon to be considered in the design is flutter, which might become a major issue for the Cradle to Cradle® aircraft design with the aluminium 6022 alloy, as Al-6022 was identified to be a less stiff material. The current section will perform a short comparison study between the flutter properties of typical aerospace alloys and the Al-6022 alloy. This analysis will be performed on the actual wing of the aircraft.

20.6.1 The Principle of Flutter

Dynamic aeroelasticity is the interaction of the aerodynamic, elastic and inertial forces with the aircraft. As part of this dynamic aeroelasticity, the phenomenon of flutter is the coupling of the aerodynamic loads with the aircraft's natural modes of vibration. The effect of flutter is a self-exciting oscillation often combined with destructive consequences for the structure. In aircraft design, especially the wings are sensitive to this failure mode.

A detailed flutter analysis comprises of two parts: an aerodynamic load case analysis and a FEM modelling of the structural system. This analysis is time consuming and difficult to be applied correctly within the timespan of the project. Therefore another, more simple method will be used to compare the flutter behaviour of both Al-6022 and the aluminium used for the Cessna Skycatcher, Al-2024. Flutter depends on the stiffness of the structure, as high structural stiffness implies higher resistance against flutter. According to the elementary beam theory, the bending stiffness is equal to the product of the modulus of elasticity E and the area moment of inertia I, as shown in equation 20.21.

$$M = EI\kappa = EI\frac{d^2z}{dy^2} \tag{20.21}$$

20.6.2 Flutter Comparison Between Al-6022 and Al-2024

Now that the principle of flutter has been explained, one can start the comparison of Al-6022 with Al-2024, a typical alloy used in the aerospace industry. From equation 20.21, one can see that both the Young's modulus and the structure's area moment of inertia influence the structural stiffness of the wing. Table 20.7 compares the bending stiffness of both options. As Al-6022 is a more flexible material compared to Al-2024, its Young's modulus is 7.5 % lower than for Al-2024. However, the moment of inertia of the Al-6022 wing becomes 39 % higher, as more material is added to the structure to compensate for the reduced mechanical properties. Therefore, the Al-6022 wing has a 29 % higher bending stiffness, from which the conclusion can be made that the structure will have less flutter issues when AL-6022 is used.

Table 20.7: Bending stiffness comparison Al-6022 and Al-2024

	Al-6022-T4 [59]	**Al-2024-T3** [61]
Young's modulus E, $[GPa]$	68	73.1
Area moment of inertia I, $\left[m^4\right]$	$1.678 \cdot 10^{-5}$	$1.208 \cdot 10^{-5}$
Bending stiffness EI, $\left[Nm^2\right]$	$11.4 \cdot 10^5$	$8.83 \cdot 10^5$

Chapter 21 | Secondary Structures

After the stress analysis of the primary structures is performed, the secondary structures have to be designed. These structures consist of "structural elements of an aircraft/spacecraft that carry only aerodynamic and inertial loads generated on or in the secondary structure" [88]. This means that those structures do not cause immediate danger upon failure. The secondary structures will be divided into four categories in the design:

- Fuel tanks
- Interior
- Doors & windows
- Remaining non-critical parts on the aircraft

The sizing for each of these structures is different. The fuel tanks can be made from aluminium or thermoplastic composites. Since the interior has to represent the Cradle to Cradle® philosophy, the material selection is different compared to the other secondary structures. For the doors & windows design, a different material will be selected compared to the remaining secondary structures. This is because the aim is to have a transparent door. All other secondary structures will be made from thermoplastic composites (TPC). These structures include the wing tips, fairings, empennage, control surfaces, spinner and spats.

21.1 Fuel Tank

From the class II weight estimation, computed in chapter 9, it has been found that the design fuel weight with its reserve equals 141 kg.
Two options were considered for the fuel tank: an Al-6022 tank or a fully thermoplastic composites tank. However, when using an Al-alloy, the effect of the reaction of ethanol with aluminium has to be investigated.

Ethanol contains soluble and insoluble contaminants. These contaminants, such as chloride-ions, affect the corrosivity of alcohol fuels. They chemically attack oxide films on several metals causing pitting corrosion and increasing conductivity of the fuel. Japanse scientific research proved that water is an inhibitor to avoid this corrosion effect. When there is enough water in the fuel, the aluminium will react with water instead of ethanol [89]. This means that the fuel tank can be made from aluminium to store the ethanol, if water is added as inhibitor. Besides protecting the tank from corrosion, the water has no other function. Major drawbacks of adding water are that the fuel weight will be increased and the fuel efficiency will decrease. Furthermore, it is not proven that the quality of the fuel remains the same after mixing ethanol with water.

Therefore, the fuel tank will be made from thermoplastic composites. Nowadays, already TPC fuel pipes are available [90], and therefore it can be assumed that it is feasible to make a complete fuel tank from this material. For the production, compression moulding can be used, as described in section 21.4. Since the loads on the fuel tanks are not critical, short fibers will be used to reinforce the structure. These reinforcements are needed to withstand sloshing of the fuel during flight. The resin that will be used is polyphenylene sulfide (PPS) because of its chemical resistance[91].

21.2 Interior Design

The pilot and passenger will spend on average 500 hours per year in the cockpit, therefore it has to be completely corresponding to the taste of the customer.
The seats will be designed using a supporting structure of the Al-6022 alloy. The seat will slide over two bars which are attached with bolts to the fuselage. Making the structure from the same alloy as the primary structures ensures that it can withstand the load of the passengers (accounting for the 6.6 g load factor as defined in section 20).

The customer can choose from different Cradle to Cradle® certified materials. There are different possibilities for both the wall covering and seating material. The same approach holds for the rest of the interior (e.g. the dashboard). A suggestion of fabrics is shown in table 21.1 [92]. It has to be noted that the flammability properties are not taken into account.

Table 21.1: Cradle to Cradle®-certified materials for interior purposes

Material	Properties	Option for wall covering	Option for seating material
Crypton Green®	100 % recycled polyester		X
Len-Tex Surface iQ	Recyclable, no chemicals	X	
Rohner Textil	Natural, fully compostable		X
Carnegie Fabrics Xorel®	85 % biobased polyethylene	X	X

21.3 Door & Window Design

This section describes the door & window design. Besides selecting a material the joining method to the fuselage structure will be discussed as well.
The door design will be based on that of the Cessna 162, but another material will be selected. The doors will be attached on their upper side to the fuselage. This means that they can be opened by swinging upward. The benefit of this configuration is that it is easy for the passenger to slide into the seat without interference from the strut or the main landing gear leg. An impression of this joining can be seen in figure 21.1. This means that the door will be attached using hinges on the upper side of the aircraft.

Figure 21.1: Door design Cessna Skycatcher [93]

It is assumed that the door does not carry any loads. However, the material of which the door consist should withstand the gust loads during flight. Therefore, a transparent polycarbonate will be selected as material. The advantage of choosing this transparent material is that the visibility increases and the weight decreases. The density of polycarbonate is 1.36 g/cm^3 [87] , compared with 2.7 g/cm^3 of Al-6022 [94]. Furthermore, the implementation of transparent structures in the design fits in the Cradle to Cradle®-philosophy. The idea behind this is that an honest product is made with respect to Cradle to Cradle®. This means that we do not have to hide something for the customer and this will be presented by the lay-out of the InfiniCraft.

Nowadays, polycarbonate is a material that is frequently used in the aerospace industry:

- HighLine Polycarbonate supplies advanced performance polycarbonate sheet for military aerospace aircraft canopies. This material is currently available to approved military aerospace contractors and is custom produced for each customer. [95]
- Total Plastics offers a range of high-performance Lexan™ and Ultem™ polycarbonates that help aircraft OEWs reduce interior weight, conserve fuel and lower emissions. These products fully comply with aircraft interior flame-smoke-toxicity (FST) regulations and aircraft manufacturer's toxicity requirements. They also enhance the aesthetics, safety and comfort of the cabin environment. These materials are made to meet the FAR requirements [96].

From these examples, it can be concluded that the design of a transparent door, using polycarbonate is feasible by 2025. Since this material is already widely used in the aerospace industry, it will also be applied as material for the window in the cockpit. This in order to reduce the amount of different materials in the design, which is beneficial for the EOL-plan, as described in chapter 24. Another advantage of polycarbonate is that it is an inexpensive material. Table 21.2 gives an overview of several Lexan™ polycarbonate sheets provided by Aircraft Spruce [97].

Table 21.2: Price of Lexan™

Thickness [mm]	Weight [kg/m^2]	Size [mxm]	Price [$]
1.52	1.85	1.22 x 1.22	35.00
2.03	2.44	1.22 x 2.44	103.75
2.36	2.88	1.22 x 1.22	58.50
0.3.175	3.81	1.22 x 2.44	123.75

Since polycarbonate is a thermoplastic polymer, it can be easily recycled, described in section G.3.

21.4 3D-printing of Remaining Secondary Structures

3D-printing is a process of making three dimensional solid objects from a digital model. This is achieved using additive processes, where an object is created by laying down successive layers of material. In all fields, from healthcare to aerospace industry, food production to clothing manufacturing, 3D printing is more advanced than many realize. But is it feasible to print the secondary structures of the InfiniCraft in 3D? An answer to this question is provided in this section.
First the 3D printing process will be described whereafter examples in the aerospace industry will be given. Next, the manufacturing & EOL plan for printed structures will be discussed. Assumptions regarding the feasibility of printing are made, therefore in case printing thermoplastic composites is not possible in 2025, compression moulding is an alternative to manufacture the secondary structures.

21.4.1 What is 3D-printing

3D-printing is a sequence of operations that are described in figure 21.2

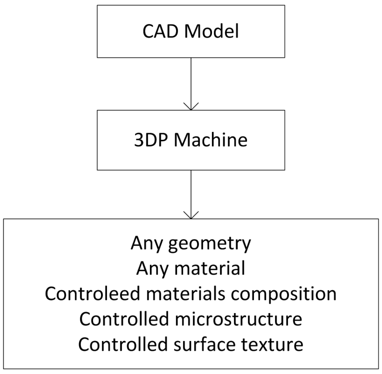

Figure 21.2: Sequence of operations of 3D printing

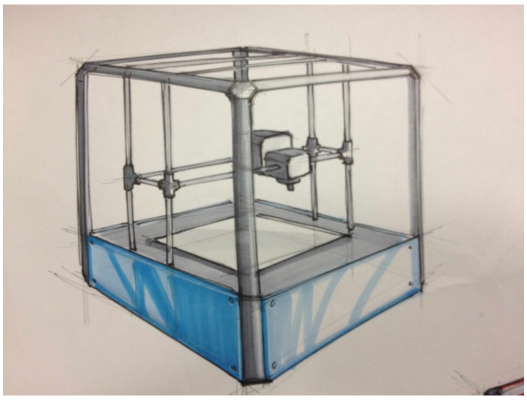

Figure 21.3: Sketch 3D-printer [98]

Software tools export 3D models as files in standard formats for 3D printing. The exported file is a mesh, or series of triangles oriented in space, that enclose a 3D volume, built-up in layers. Each layer is produced starting with a thin distribution of powder spread over the surface. A binder material selectively joins particles where the object is to be formed. A piston that supports the powder bed and the part-in-progress lowers so that the next powder layer can be spread and selectively joined. This layer-by-layer process repeats until the part is completed. Following a heat treatment, unbound powder is removed, leaving the fabricated part. An impression of a 3D-printer can be seen in figure 21.3. This means that if a Catia-drawing of the secondary structures is made, it can be printed, with the assumption that printing thermoplastic composites is possible in 2025.
The benefit of this process is that it can be done locally. This means when a secondary structure such as a wing tip has to be replaced, it can be done in a quick way, where less transport is involved. Just a Catia-drawing of the part has to be send to a local manufacturer (eventually the airport itself), and they can print and install it on the InfiniCraft.

21.4.2 3D printing in Aerospace industry

In all industries, 3D printing is an upcoming manufacturing technology. The following list gives an overview of several 3D-applications in the aerospace industry:

- Stratasys and Autodesk build the first 3D-printed full-scale turbo-prop aircraft engine model [99].
- Airbus has been bullish about its future plans around using 3D printing as part of their manufacturing processes with a goal of making the entire aircraft from ground up with giant 3D printers by 2050 [100].
- Even in space applications 3D printing is an upcoming technique: NASA engineers use 3D printing to build a next-generation rover to support humans exploring other worlds, such as asteroids and, eventually, Mars [101].

It can be concluded that the main players in the aerospace industry are already going to apply 3D-printing in their design. This means that this manufacturing technique is a great opportunity for the future.

21.4.3 Manufacturing & EOL

Three thermoplastics are available for use by the aerospace industry: polyphenylene sulfide (PPS), polyetherimide (PEI) and polyetheretherketone (PEEK). From these has been found that PPS has the lowest cost. Applications of PPS composites in aircraft include the undercarriage door of the Fokker 50, fixed wing leading edges for the Airbus A340 & A380 and others. PPS is a high performance thermoplastic, which is extremely strong, rigid and tough. It offers inherent flame resistance, high heat resistance at temperatures well above 200$°C$. It also has very good chemical and oxidation resistance, minimal water absorption, good electrical properties, low creep and excellent mechanical properties. [102]
It has been found that high performance PEEK material is already used for 3D printing. No research has been found about printing PPS but since PEEK can be 3D-printed nowadays, it can be assumed that PPS parts can be printed for the aircraft in 2025 [103].
Short fibers will be used to reinforce the structure for two main reasons. As defined, secondary structures carry only non-critical, aerodynamic and inertial loads. Therefore, short fibers are sufficient to reinforce those structures. The second reason is that the nozzle diameter of 3D-printers is small. Therefore it is not feasible to print long fibers. Nowadays, several companies are already selling fiber-reinforced plastic with excellent stiffness, strength and temperature resistance. Duraform HST Composite ® is an example of that. The properties of this material can be found in Appendix D.
The recyclability of this material is also of great importance. If a structure fails, it has to be possible to re-melt the material, and print it again. Thermoplastic matrix composites can be recycled directly by remelting high value materials.

21.4.4 Compression moulding

Since assumptions are made concerning the possibility of printing thermoplastic composites, compression moulding is proposed as alternative if 3D printing turns out not be feasible in 2025.
Compression moulding is a high-volume, high pressure process suitable for moulding complex reinforced parts using either thermoset or thermoplastic resins. The principle of compression moulding is described in figure 21.4.

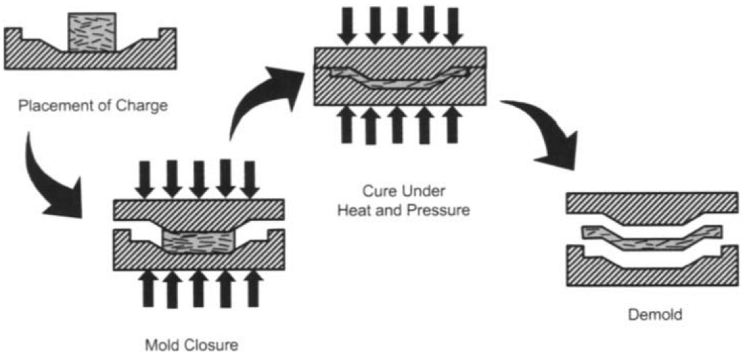

Figure 21.4: Principle of compression moulding of thermoset composites [104]

The short fibres drift with the resin until the whole die cavity is filled. The resin flow dictates the forming operation. Since this tooling is very costly, it is not frequently used in the aerospace industry. In the automotive industry, this process is used extensively due to the mass production [105][104]. This leads to another disadvantage, which is that compression moulding cannot be done locally due to the special and expensive tools.

21.4.5 Production process for first design

As described in chapter 27, the production of the aircraft will happen in one central production plant. Since 3D-printing is a time-consuming process, all thermoplastic composites will be produced using compression moulding in its first phase. When maintenance has to be done on the aircraft, those parts can be printed locally.

Chapter 22 | Structural Joining

Smart joining methods can significantly reduce maintenance complexity and benefit end-of-life solutions. In this chapter, a detailed description will be given on the used joining methods and the application of them. A description of the different relevant joining methods is given in appendix C. An assessment is done on each of these methods to select the appropriate ones. Then, an analysis will be performed on the aircraft structure to determine what methods shall be applied to which structural elements. Finally, the total economic and ecological impact of the structural joints will be assessed and compared to current aircraft.

22.1 Joining Methods Selection

Welding, mechanical joining and adhesive bonding were considered as joining methods. After assessing all the different joining methods as described in Appendix C, a decision can be made on the type of joining methods that will be used in the design. In the next section each of the selected methods will be described in more detail, focussing on their general purpose in the design.

22.1.1 Friction Stir Welding

Friction Stir Welding (FSW) will be applied to components that are designed for safe-life. This means that they do not require replacements during their lifetime. Looking at fatigue, it should be noted that FSW has a small effect on the yield strength. For example, Al-6013-T4 encounters a reduction in yield strength of maximum 5% around the weld [106].

22.1.2 Riveting

As described in the previous subsection, welding is not applied to maintenance sensitive areas. Riveting is a good substitute joining method for these places. Rivets can easily be drilled out so that the panel (or other structural component) can be removed. In case of an incident, the underlying airframe can then be inspected and damaged panels can directly be replaced by new ones. For the Cradle to Cradle® philosophy it would be perfect if the sheet metal and rivets can be made from the same material. This reduces the disassembly time at EOL since the rivets do not have to be removed.

Typically, Al-2024-T3 is used to manufacture rivets due to its good fatigue crack growth resistance. The disadvantage of this alloy is that it is a precipitation hardened alloy and therefore a special treatment is required: When using Al-2024-T3, the rivets are placed in a freezer after manufacturing to prevent them from precipitation hardening. They can then be removed from the freezer and installed, then left to age in their installed state. Using this material introduces additional issues of limited shelf-life of the rivets and the added complexity and processing constraints around freezing the rivets.
Another common rivet material is Al-2117. This is an alloy of aluminium and copper where corrosion resistance is fair and which hardens over time. However, the forming and strength charachteristics are good [107]. The last rivet material which is considered is Al-6022. This is the same material as the primary structures and therefore this is beneficial for recycling opportunities. A comparison of Al-2117 and Al-6022 can be found in table 22.1 [59][107].

Table 22.1: Comparison 2117 with 6022

	Al-2117	**Al-6022**
E [GPa]	71	68
σ_{ult} $[MPa]$	241.25	271
σ_{fat} $[MPa]$	96.5	108
σ_y $[MPa]$	165	160
ρ $[kg/m^3]$	2740	2700
$price$ $[e/kg]$	3.5	6

22.1.3 Bolting

Bolts are installed on locations where accessibility is very important. Engine parts, doors and hoods are all connected using bolts. These are often moving parts that need regular maintenance. Bolts however increase the overall weight of the structure due to the structural reinforcement required at the joining location.
Aircraft quality bolts are made from alloyed steel, stainless or corrosion resistant steel, aluminium alloys or titanium. The first two are the most common. Standard bolts used in aircraft construction are AN3 through AN20. AN means the bolt is manufactured according to Air Force-Navy specifications. Further explication about the AN-bolts and their specifications can be found in Appendix C.

22.2 Application of Joining Methods

In this section, an overview is given of each structural group in the design. This overview defines the joining method between all the elements within a structure and the joining between the different groups.

22.2.1 Wing Group

Table 22.2 presents the joining methods used in the wing group. As can be seen, the primary structure will be riveted to each other. This is similar to most wing box structures since this gives the opportunity to drill the rivets out to inspect the quality of the underlying structure.
The wing will be bolted to the fuselage, together with the strut. This is done in order to reduce the assemble and disassemble complexity. The secondary structures, like the leading edge, will have to be replaced during the lifetime of the aircraft. Therefore, bolts are used for this elements. A similar joining technique is used to connect the control surfaces with the wing structure.

Table 22.2: Wing group joining methods

Element	Joining method
Primary structure	Riveted
Fuselage attachment	Bolted
Secondary structure	Bolted & Riveted
Control surfaces	Bolts
Strut	Bolted

Table 22.3: Fuselage group joining methods

Element	Joining method
Door & windows	Bolted
Interior	Bolted & Welded
Skin	Riveted
Fireplate	Welded
Strut	Bolted
Longerons	Riveted

22.2.2 Fuselage Group

The structures which are connected within the fuselage are listed in table 22.3. The first attachment to be considered is the connection of the window and door to the fuselage structure. These are made of polycarbonate, which should then be attached to aluminium. The window will be attached to a frame which is connected to the fuselage. Bolts will be used to put the window in the frame, and to attach the frame to the fuselage. This means that when the window is damaged due to an impact, it can easily be replaced. The cockpit is one of the main elements in the fuselage structure. This includes the interior where the seats are attached to rails. Those rails will be welded to the fuselage floor. The skin around the fuselage will be riveted to the primary structure, similar to the wing skin. The fire plate which protects the cockpit from the engine is attached using welding. This plate may not move or vibrate during flight and therefore welding is used. The strut connecting the wing with the fuselage will be bolted to the fuselage structure.

22.2.3 Landing Gear

The wheelbase will be bolted to the strut which connects the wheel with the fuselage. The strut is considered as a primary structure and will be welded to the fuselage, for both nose and main gear. The used joining methods are displayed in table 22.4.

22.2.4 Propulsion Group

The parts in the propulsion group will be bolted to each other, in order to be able to inspect all parts of the engine group. The considered parts are the nacelle, engine mount, propeller mount and spinner, which can be found in table 22.5.

Table 22.4: Landing gear joining methods

Element	Joining method
Wheelbase	Bolted
Primary structure	Welded

Table 22.5: Powerplant joining methods

Element	Joining method
Nacelle	Bolted
Engine mount	Bolted
Propeller mount	Bolted
Spinner	Bolted

22.2.5 Tail Surfaces

The used joining methods for the empennage are described in table 22.6. The horizontal tail will be clicked to the empennage like in a glider configuration. Bolts will used for the joining. The vertical tailplane will be welded to the structure. Since the rudder and elevator have to move freely, they will be bolted using a hinge.

Table 22.6: Empennage joining methods

Element	Joining method
Horizontal tailplane	Bolted
Vertical tailplane	Welded
Rudder	Bolted
Elevator	Bolted

22.3 Economic and Ecological Impact

After assessing the application of the joining methods on the aircraft structure, it is important to consider the economic and ecological impact of these techniques in order to validate the Cradle to Cradle® aspect of the aircraft design.

The economic and ecological impact can be subdivided into four main catagories: waste, manhours, energy use, required amount of material and maintainability. The latter criterion is included as it is of key importance to the final design. In the end, an easily maintainable joining method reduces the economic and ecological impact.
A qualitative analysis has been performed to rate each of the joining methods on these criteria.

Table 22.7: Joining methods impacts

	Waste	Cycle time	Energy required	Required material	Maintainability
Riveted [108]	-	-	+	-	+
Bolted [109]	-	-	+	-	+
Welded [110]	+	+	-	+	-

Looking at table 22.7, riveted and bolted joints show similar impacts on the design. A major difference is the waste produced when riveting. This is mainly due to the large amount of holes that need to be drilled where both rivets and bolts will be put in. However, this waste can be caught and be reused after melting as new Al-6022. These methods require little energy and have excellent maintenance properties, as the removal and inspectability of these joints can be done easily.
It can be seen that each joining technique has its own advantages and all will be implemented in the design.

Chapter 23 | Wiring & Electronics

In this chapter the wiring and electronics of the aircraft are discussed. First the core material for the wiring will be selected, second the wire insulation material will be chosen and finally the electronics and avionics are investigated.

23.1 Wiring

Currently most wires and connectors in electrical equipment are made from copper or aluminium. For many years both materials are used continuously in the electrical industry. Also silver is sometimes applied in electrical circuits, however due to its high cost and low strength the application is limited. To be able to select a material from the remaining two, one has to compare both electrical and mechanical properties of the materials. The conductivity, the weight, the material expansion and the material cost are compared. In table 23.1 a comparison can be seen between copper and an aluminium alloy. The data is retrieved from GE Industrial Solutions [111].

Table 23.1: Properties of copper (UNC C11000) and aluminium (Al-1350)

Characteristics	**Copper**	**Aluminium**
Weight for same conductivity [kg]	100	54
Cross-section for same conductivity [m^2]	100	156
Specific resistance [$n\Omega \cdot m$]	17.6	30.8
Coefficient of expansion [$°C \cdot 10^{-6}$]	16.6	23.0

As seen in table 23.1, the conductivity of copper is 56% higher than that of aluminium. Which means that the cross-sectional area of the aluminium alloy has to be 56% larger. This volume increase may be a point of attention, when the space is limited. Taking into account the density of the material as well as the conductivity ratio, one may find that the amperage capacity of aluminium is 1.85 times that of copper. This leads directly to the weight aspect. The 1.85 factor can be seen as follows: one kilogram of aluminium has the same electrical capacity as 1.85 kilograms of copper. Hence, a weight reduction of 54% can be achieved when using aluminium. In terms of expansion, aluminium has a 42% greater expansion coefficient. This does not directly lead to problems, however special care has to be given to the joining locations. If wires are attached with little margin, shrinkage & expansion of the material may cause failure.

The material prices of copper and aluminium causes the price difference to fluctuate. Also prices of conductors stimulate this fluctuation. Switchboards are generally 25-30% cheaper if the bus is from aluminium, rather than copper. Prices for transformers are 45-100% higher for copper windings [111].

The above comparison provides a proper foundation to select aluminium as core material. The insulation material still has to be chosen. In aviation, Polyvinyl chloride (PVC) is prohibited due to flammability issues [112]. Also the recyclability of PVC is very limited due to the toxic gasses that arise when melting the material. Recently, RS Components Ltd. unveiled the EcoWire [113]. The insulation is fully recyclable, while maintaining the same (or better) functionalities. The insulation is based on Noryl, a modified polyphenylene (mPPE). No halogens nor pigments are added, allowing to meet Waste Electrical and Electronic Equipment (WEEE) requirements. The insulation is therefore certified to be recyclable. mPPE is inherently lighter than PVC, tougher and more flame resistant [114].

23.2 Avionics and Electronics

The avionics and electronics in an aircraft take up a significant portion of the aircraft's OEW. From the class II weight estimation it can be seen that flight controls and IAE (Instrumentation, Avionics and Electronics) take up about 61 kg or 15% of the OEW. Since electronics are generally hard to recycle according to the Cradle to Cradle® principle, new ways should be found in recycling electronics to comply with the 90% recyclability requirement.

There are six basic instruments that need to be included in every cockpit. There are three gyroscopic instruments and three air data instruments. The instruments can either be analogue or digital. Apart from these basic instruments, there are several other (electrical) components found in a cockpit. These include the transponder (radio), the intercom system and fuel indicators.

The gyroscopic instruments are the following [115]:

- The artificial horizon (attitude indicator), shows the attitude of the aircraft with respect to the surroundings.
- The heading indicator, works like a compass and is used to navigate.
- The turn and bank indicator, indicates how a turn is flown; too much or not enough rudder.

The air data instruments are the following:

- The airspeed indicator, determines using the dynamic pressure the velocity of the aircraft.
- The pressure altimeter, uses the static pressure to measure the altitude.
- The vertical speed indicator, measures the climb and decent rate using the static pressure.

23.2.1 Mobile Devices

A recent development in the aviation industry is the application of mobile devices as avionic systems. Many pilots nowadays already fly using their mobile devices, although this is in general not allowed by regulations (see figure 23.1). The benefits of flying with mobile devices are:

Figure 23.1: iPad® used in general aviation [116]

- Up-to-date software: new technologies can quickly be applied since no avionic systems need to be replaced, just the mobile device should be replaced or updated.
- The computer does not have to be on-board the aircraft. Since a tablet or smartphone has enough computing power to display the data that is currently showed on on-board avionics, the system weight can be reduced. Any check-lists that are normally hard-copies can also be viewed on the mobile device.
- With mobile devices it is possible to change the layout of the avionics. This is an extra added value for training purposes; different cockpit layouts can be modelled.
- The expensive electronics can be taken out of the aircraft, to avoid theft.

Recently the Federal Aviation Administration (FAA) approved a new aviation mapping application for the iPad® that allows the charter company Executive Jet Management to use the iPad® for electronic mapping within the cockpit on the company's flights [116]. The decision of the FAA suggest that the FAA is acknowledging the potential for tablets to replace avionics instruments.

23.2.2 Wireless Sensors

Another development is the use of wireless data transfers from sensors to cockpit. Data from GPS, pitot tubes and subsystem information can be sent over Bluetooth to the cockpit, where it can be displayed on a mobile device. This will again save weight, since wires can be omitted [117].

The general idea is to keep the aircraft as simple as possible. The calculating power can come from mobile devices brought by the pilot. In the end, this can save the weight of the IAE and other electrical subsystems, which is approximately 50 kg or 7% of the OEW (from the class II weight estimation). This method also fits in the Cradle to Cradle® philosophy, as less material is used and the amount of low-recyclable electronics is reduced.

Chapter 24 | End-of-Life Plan

At the end-of-life of the aircraft, it needs to be disassembled and recycled. When reusing these recycled materials, the Cradle to Cradle® material cycle is closed. The end-of-life plan is a valuable tool in this process since it describes the dismantling of the aircraft and the handling of the obtained materials.
In the first section, current EOL plans will be assessed. In the second section, the disassembly of the InfiniCraft will be described. In the next section, the disassembly methods per joining method will be discussed. Thereafter the re-utilisation of specific parts will be discussed and finally the last section will elaborate on the processing of the disassembled aircraft materials.

24.1 EOL Plan of Current Aircraft

For a long time, recycling has been a neglected topic in the aviation industry. Due to the booming of civil aviation in the 1970s and an approximated life span of 30 years for an aircraft, EOL plans started to be investigated in the 2000s. Before that, once aircraft reached their EOL, they were generally converted as a cargo aircraft or stockpiled in aircraft "graveyards". Until now, there are no governmental regulations for the handling of EOL aircraft. The aviation industry is only indirectly affected by existing regulations. For example, the handling of electronic scrap has to be carried out according to existing laws [118].

Nowadays, projects that focus on the recycling of aircraft are already in effect. The PAMELA (Process for Advanced Management of End- of- Life of Aircraft) project, initiated by Airbus and EADS, aimed at designing a process that can be used to recycle and reuse the rising number of decommissioned aircraft in an environmental friendly way [119]. The PAMELA project extracted 61 000 kg from the Airbus A300 which implies that only 13 % of the original weight of the aircraft had to be classified as non-recoverably waste and sent to landfill. However, this project did not focus on the Cradle to Cradle® principle since most materials are not reused at the same level of quality.
Another example is the Aircraft Fleet Recycling Association (AFRA), a cooperation of Boeing with more than ten European and American companies. Its goal is to find a self-financing nonprofit organisation whose members work corporately according to a certificate of approval in the area of aircraft vehicle disposal [118].

The automotive industry can be seen as a model for the aviation industry when it comes to end-of-life. Typical procedures in this sector are as follows [120]:

- Electro-mechanic parts are usually remanufactured and resold
- Structural body parts are usually used in repairing accident-damaged vehicles. This is something which can also be implemented in the aerospace industry, however the main focus in our vision is that the body will be remelted and reshaped for a new aircraft.
- Vehicle fluids like oil, transmission fluid etc are recycled [120].

It can be concluded that the EOL phase of aircraft can no longer be neglected as the amount of aircraft will increase in the future. Today, Boeing & Airbus are already doing research, but the end-of-life strategy in general aviation is still limited. Similar to the aluminium selection, the automotive industry is a model for the EOL-procedures of the InfiniCraft.

24.2 Disassembly of the Aircraft Structures

In this section the disassembly of the aircraft structure is described. During the disassembly, the safety of the labourers is of primary importance. It is hence very important to mount the aircraft and to secure all structures before starting the disassembly. The aircraft should be clamped at its landing gear and also the empennage and wings should be clamped to ensure safe and easy disassembly.

The first phase in the disassembly is the decommissioning of the aircraft [121]. In this phase, all the flammable and dangerous substances will be removed. These include trapped fuel in the fuel tank and in the lines from the tank to the engine. Engine oil and a coolant is used in the engine itself. Furthermore oil is used for the brakes of both the nose and main landing gear ass well as in the nose gear shock absorber. All substances need to be tapped off and need to be stored in separate volumes.

The next phase is the disassembly of the aircraft structure. First, all external structures will be stripped off. Next, the remaining non-primary structures will be disassembled. Finally, the wing and fuselage structure will be treated.

Control surfaces: These are made from short fibre thermoplastic composites. They are hinged with bolts to the wing and tail structures. To remove these structures from the aircraft, the bolts need to be loosened and the control cables need to be taken off the control surfaces. The materials obtained from this process consists of steel bolts and thermoplastic composite panels.

Flaps: The flaps can be disassembled by putting them in landing configuration and unbolting them from the flap movement structure. The control cable needs to be detached before the flaps can be taken off.

Propeller and engine: The propeller is made of wood and can be fully recycled. The spinner in front of the propeller is made from thermoplastic composites. The engine is mounted to the front of the fuselage using bolts. Some rubber is also required to reduce the vibration transfer from the engine to the fuselage. An analysis of the engine and its various components is given in section 15.2.

Doors and windows: The next step is to take out the doors and windows, which provides easy access to the interior. As described in section 21.3, the door and windows are made from polycarbonate panels. Doors are hinged to the fuselage and are hence easy to be taken off. The windows are placed in an aluminium frame which is secured with steel bolts to the fuselage structure.

Interior and instruments: The interior and instruments were installed as one of the last components during the assembly of the aircraft. They can easily be removed with regular tooling equipment. The whole dashboard can be taken out and can be disassembled into smaller components. The seats will follow the same procedure. Next, the flooring and rudder pedals are taken out. Finally any remaining interior is taken out of the aircraft so that only the cables and the primary structure are left. The obtained materials in this step of the disassembly process are all Cradle to Cradle® certified materials as specified in section 21.2.

Antenna and lights: Next the antenna, the navigation lights and beacon light will be removed. The antenna (made from steel) is situated at the back of the fuselage. The cable needs to be loosened and the antenna can be taken off the aircraft. Lights are situated at three places on the aircraft. At the wing tips, navigation lights can easily be accessed to detach. Also the beacon light at the tail structure needs to be disassembled. The last light to be disassembled is the landing light which is situated in front of the fuselage underneath the (already removed) engine. The light can be removed and the wires need to be unplugged. These will be removed in the next step.

Control cables and electronic wiring: Now that the cabin is empty the control cables can easily be taken out, since the controls and control surfaces are already removed from the structure. The control cables are made from steel as discussed in chapter 12. The pulleys in the fuselage can also be disassembled. These will be made from aluminium to provide easy joining and disassembly.

Empennage: The aircraft structure is now stripped of all non-aluminium elements. First the horizontal tail surface will be disassembled. It is fastened with bolts based on the glider principle (section 22.2). The vertical tail surface is welded to the fuselage structure. It will be removed by cutting the fuselage just before the tail section with a saw. This disassembly technique is described in the following section. As stated in the introduction, the safety of the workers is of primary importance and hence the empennage should rigidly be clamped before the cutting starts.

Wing: The wing and wing strut are bolted to the fuselage. When the wing is rigidly clamped at the two tips, the bolts on the wing-fuselage and the wing-strut joint can be loosened and the wing can be separated from the aircraft. Next, the wing needs to be lowered, and the skin can be detached from the stringers to take out the fuel tanks and remaining electronic and control cables. The remaining flap structure in the wing consists of aluminium pulleys and can be left in place. The wing will be cut in smaller pieces to provided easy processing in the next disassembly phase. The strut is bolted to the undercarriage of the fuselage and can also be removed easily.

Landing gear: The landing gear is composed out of an aluminium strut and a rubber tire, reinforced with steel wire. The strut is welded to the fuselage. In order to remove it, the strut is sown off. The rim of the tire is made from aluminium and can be removed by removing the bolts.

Fuselage: Now only the basic fuselage structure is left. It is stripped of its wings, empennage and landing gear. Also the propeller and engine, the interior and all electronics and controls have been removed. The fuselage can now be clamped at the front and the back of the aircraft and on the remaining center wing box structure. It will be cut into circular pieces of approximately 1.5 meters wide. Attention should be paid to the fact that no cuts are made directly on the stiffeners. For the safety of the saw operators, cuts should be started at the bottom of the structure and end at the top so that no materials may fall onto the operator.

24.3 Disassembly Methods

The methods used for the disassembly of the structure are mainly influenced by the applied joining method. Therefore different disassembly techniques have been analysed in appendix E for both welded and riveted joints.

24.3.1 Welding disassembly

The primary structure will be disassembled using manual sawing. The main advantages of this technique, as explained in appendix E, are its low energy consumption and cheap processing cost.

Even though different sawing techniques exist, a classic circular saw will be used (figure 24.1). This sawing technique provides the most optimal accessibility, as this is a major requirement for the disassembly of the complete aircraft structure. The whole sawing process can be executed by two people to ensure a safe and quick operation. A shielding of the saw will be required in order to protect the operator, which can also be seen in figure 24.1. Both the wings and empennage will be separated during the sawing process.

Figure 24.1: Circular saw

24.3.2 Rivet disassembly

As discussed before, the rivets used for the mechanical joints will be made from the same Al-6022 alloy as used for the primary structure. Therefore disassembly of the riveted joints becomes not needed. The riveted structures will enter the remelting phase without removal of the rivets.

24.4 Re-utilisation of Parts

In the previous sections, the aircraft disassembly is described. Various parts, fluids and materials are obtained in this process. Some of these parts can be re-used in new aircraft.
Special inspection should be paid to the selected parts, so that it is certain that they can be used in the new aircraft or as spare parts for maintenance replacements, meaning they need to be recertified. If needed, a maintenance session will be required to use them again.

Control surfaces can be reused for replacements during maintenance. These structures are easily damaged due to bad handling in the storage of the aircraft or due to normal wear during use. The parts can then be used as a cheap and easy replacement for broken ones.
A **propeller** is a part that can easily be damaged. However, a propeller from an EOL aircraft that still meets the requirements be placed on another aircraft during a maintenance session or even during the design of a new aircraft.
The **engine** will be returned to the manufacturer every 2000 hours for an overhaul as described in chapter 15. It will therefore not be used for replacements in other aircraft.
Doors and windows carry no loads and hence are not sensitive to fatigue. After inspecting the polycarbonate material on cracks, cuts and other degradations, they can be used again in other aircraft.
The **instruments** from an EOL aircraft can be used in a new aircraft on the conditions that no major updates in the avionics have been developed yet. The instruments need to be carefully extracted from the dashboard and recalibrated in the new aircraft.
Antennas and lights can be used again, as long as they still have the same properties and functionalities as required.
If the **landing gear** is cut off in a secure way, it can be attached to a new aircraft or to an aircraft that experienced a hard landing with a landing gear failure as consequence.

24.5 Processing of the Obtained Materials

Now that the aircraft is disassembled and all materials are separated on the ground, they can be grouped together and processed to close the material Cradle to Cradle® cycle. Some parts can be reused for multiple life cycles as explained in the previous section, but eventually, all components will need to be recycled. The following materials and parts are obtained from the aircraft:

- Motor fluids
- Short fibre thermoplastic composites
- Polycarbonate panels
- Wooden propeller
- Engine
- Interior
- Instruments
- Electric wiring
- Lights
- Rubber
- Aluminium structure, panels, rails ...
- Steel cables, bolts and antenna

The detailed recycling process for each of these materials is described in appendix G.

24.6 Recycling Rate

One of the requirements was to come up with a design that is 90% recyclable. In order to prove this, the ratio of the recycled mass and the operative empty weight will be computed. If this ratio equals or exceeds 90%, the requirement is met. If not, it can be concluded that in 2025, it is not feasible to recycle a general aviation aircraft built with our design choices. Before assessing the recycling rate (RR), it is important to perform an update on the class II weight estimation. The weight of the components in the InfiniCraft can be found in appendix F. The coating weight was estimated by calculating the wetted surface of the InfiniCraft and multiplying it with a typical coating thickness of 0.1 mm and density of 1 200 $^{kg}/_{m^3}$ [122] [123].

Table 24.1 shows the recycling rate of the materials & components used in the InfiniCraft. These rates are based on the recycling properties of each material, as discussed in appendix G.

Table 24.1: Recyclability of the InfiniCraft materials

Material	**RR** [%]	**Explanation**
Aluminium	100	Aluminium maintains its properties after recycling.
Thermoplastic composite	100	With the novel techniques used, thermoplastics composites are assumed to be fully recyclable in 2025.
Steel	100	The recycling process of steel is similar to that of aluminium.
Polycarbonate	95	Plastics have good recycling properties. However, still some losses occur.
Rubber	80	Natural rubber has good recycling properties, but other materials are implemented as well, however with lower properties.
Wood	100	Wood is biodegradable and can therefore be fully recycled in the bio-cycle.
Engine fluids	95	The fluids can be filtered, and therefore only small losses occur.
Engine block	87	The engine will be resold to other parties after 2 000 hours of operation. After an intensive process, 87 % can be recycled.
Electronics	87	In general most of the electronic components can be recycled, but difficulties exist on the disassembly of the circuit boards.
Mechanical instruments	90	Mechanical instruments can be reused in other aircraft and afterwards disassembled in its components. Some materials have better recyclability performances than others.
Lights	95	Lights will be reused again due to its long lifetime. In the end 95 % is recyclable.
Wiring	100	Wires are good recyclable after the insulation and the aluminium are stripped.
Interior	100	The covers in the interior are Cradle to Cradle® certified combined with an Al-6022 structure.
Coatings	0	The coatings are removed in order to recycle the aluminium. They are chemically removed and can not be recycled.

It has to be noted that the materials can not always be fully recycled since several losses will occur during processing. These losses have several causes.

- The sawing of the InfiniCraft into several parts.
- Losses during the removal of the trapped fluids.
- Losses of bolts, washers and other parts of the aircraft.
- General difficulties and other losses during the disassembly process.

As a result, a correction factor of 98 % will be applied in order to account for these losses.

The next step is to define the amount of material per component. For example, it is assumed that the wing structure consists of 72.8 % of Al-6022, for 20.0 % of TPC, for 4.0 % of steel and for 3.2 % of paint. For each component, these mass fractions are determined in appendix H. When the weights of each material are summed, the values in the third column of table 24.2 are obtained. In the second column the recycling rate including the correction factor can be found. The fourth column represents the relative weight of the materials compared with the OEW. The fifth and sixth column display the amount of recycled material and waste. From the table it can be seen that 380.3 kg or 93.4 % of the aircraft's OEW can be recycled. This means the main project requirement is met.

So far, no distinction was made between up- or down-cycling. The materials that can be recycled with respect to the Cradle to Cradle® principle are marked with a '1' in the seventh column of table 24.2. The non-Cradle to Cradle® recycled materials are marked with a '0'. When summing up the up-cycle column, it can be concluded that in total 361.1 kg of the OEW can be recycled with respect to the Cradle to Cradle® philosophy. This corresponds to 88.7 % of the OEW.

Table 24.2: Recyling rate calculations for the InfiniCraft materials

						Cradle to Cradle® recycling		
Material	**RR**	**Weight**	**% OEW**	**Recycled**	**Waste**	**Yes/No**	**Upcycle**	**Downcycle**
	[%]	[kg]	[%]	[kg]	[kg]	[−]	[kg]	[kg]
Aluminium	98,0	203,5	50,0	199,4	4,1	1	199,4	0,0
TPC	98,0	19,2	4,7	18,8	0,4	1	18,8	0,0
Steel	98,0	7,7	1,9	7,5	0,2	1	7,5	0,0
Polycarbonates	93,1	6,2	1,5	5,8	0,4	1	5,8	0,0
Rubber	78,4	4,8	1,2	3,8	1,0	0	0,0	3,8
Wood	98,0	13,8	3,4	13,5	0,3	1	13,5	0,0
Engine fluids	93,1	3,2	0,8	3,0	0,2	1	3,0	0,0
Engine block	85,0	60,2	14,8	51,2	9,0	1	51,2	0,0
Electronics	85,6	18,0	4,4	15,4	2,6	0	0,0	15,4
Mech. instr.	88,2	12,0	2,9	10,6	1,4	1	10,6	0,0
Lights	93,1	11,4	2,8	10,6	0,8	1	10,6	0,0
Wiring	98,0	7,6	1,9	7,4	0,2	1	7,4	0,0
Interior	98,0	34,0	8,4	33,3	0,7	1	33,3	0,0
Coatings	0,0	5,5	1,4	0,0	5,5	0	0,0	0,0
			Total:	380,3	26,7		361,1	19,2
			[%] OEW:	93,4	6,6		88,7	4,7

PART V

OPERATIONS & LOGISTICS

"Design is not just what it looks like and feels like. Design is how it works."

Steve Jobs,
Co-founder of Apple Inc.

Chapter 25 | Unit Cost

In this chapter an overview will be given of the estimated unit cost of the InfiniCraft. This needs to be done to achieve a dry lease price. This lease price will cover only the unit cost, so no operational costs are included in this price. Details of the calculations can be found in appendix I.

25.1 Unit Cost Estimation

To calculate the unit cost of one airplane, the method of Roskam is used [124]. Two main categories are analysed: the research, development, test and evaluation costs and the acquisition cost. The first involves all the costs for designing and testing the InfiniCraft before it can actually be built. Afterwards the costs for building the airplane are listed. Adding these two categories together will give a price for making all the airplanes (500 + 2 test airplanes will be produced). This cost is divided by the amount of airplanes and will result in a unit price for one InfiniCraft. Detailed calculations can be found in appendix I. The most important parameters are listed and discussed here.

Research, Development, Test and Evaluation Costs (RDTE)
In the equations of Roskam, a lot of parameters need to be filled in. They include characteristics of the airplane like maximum speed, take-off weight, number of engines and number of propellers. These all come from the initial sizing and the requirements for the project. Some other important parameters are the costs for the engineers and the workers. These are estimated to be respectively $ 50 and $ 10 per hour [125]. Other parameters are correction factors. These factors account for new materials, new facilities and extra complexity. In this section, also the required profit and interest rate are included. In the end this gives a total price of $ 2 868 448 for 502 aircraft, which will contribute $ 5 714 to the final unit cost.

Acquisition Costs
The acquisition costs contain all the the major costs to build the airplane are taken into account. These consist of factors like engineering and worker costs. All material prices are based on the average price of different manufactures. Also interior cost, number of passengers, manufacturing rate and tooling labour rate are included. The final acquisition cost is estimated at $ 87 026 789 for all the airplanes, which will contribute $ 173 340 to the final unit cost.

Total Unit Cost
Now that the RDTE costs and the acquisition cost are both known, the total price can be calculated. The two prices are summed to a total of $ 89 885 237. Given the fact that 500 aircraft will be sold, the price for one aircraft will be $ 179 530. Although this is over the planned budget for the InfiniCraft, this aircraft has some other advantages. This advantage lies in the operational cost, which will be further explained in chapter 26. Based on this unit cost, a lease plan is worked out. This dry lease price and the whole concept of the leasing program will be further explained in section 25.2.

Calculation Accuracy
It has to be noted that the calculations done in this section are based on the Roskam formulas which mainly uses reference aircraft. The InfiniCraft makes use of new techniques and materials which are different from existing aircraft. This means that it can be assumed that this cost estimation is not very accurate, however it can be seen as a preliminary estimate. The following factors can be taken into account in a more extended cost analysis:

- **Rivets:** As part of the EOL-plan, the rivets of the InfiniCraft are made from the same material as the aircraft itself. This is to ease the dismantling. However, as these rivets will be more expensive than the existing ones, they need to be implemented in the cost estimation.
- **Higher empty weight:** Due to the lower strength to weight ratio of Al-6022, the aircraft structure will be heavier. This means more material needs to be used, which will increase the cost. However, this alloy is cheaper than the standard aviation alloys, so it will also be cheaper. Both of these factors need to implemented in a detailed cost estimation.
- **Ethanol conversion kit for the engine:** To make sure that the engine can run on ethanol, a conversion kit needs to be installed. This conversion will cost money and this needs to be taken into account. Now only the costs for a normal engine are accounted for in the cost estimation.
- **Higher safety margins due to new materials and techniques:** Due to the new techniques and materials that are used (for example the thermoplastics, new rivets and welding techniques), safety margins will be higher. These safety margins will cause the unit cost to increase as a result of the increased structural weight.

- **Thermoplastic materials:** The thermoplastics that are used for the secondary structures will be more expensive than normal aluminium components.

25.2 Dry Lease Price

For the InfiniCraft a leasing construction will be used. The reason for this is twofold. First of all, leasing the aircraft makes sure that the aircraft will come back at the end of its contract, guaranteeing that the aircraft can always be disassembled and re-used according to the Cradle to Cradle® philosophy. Secondly, the initial production costs of the aircraft can be higher due to the end-of-life value of the aircraft.

For the organisational construction a dry-lease contract is used. The reason for this is that this contract closely resembles the actual buying of an aircraft, since maintenance and operation is the responsibility of the lessee. One of the major purposes of the InfiniCraft is leisure or training. These customers use their aircraft frequently (400 to 600 hours per year) and have the capabilities and capital to maintain and operate their aircraft themselves as if it was a fully owned aircraft.

The duration of the contract can be varied, depending on the customer's wishes and the economical environment. To illustrate this, four different contracts have been developed. Dry lease prices for three of these contracts are shown in table 25.1. The hourly dry lease prices have been calculated for 500 annual flying hours. The fourth contract will be explained later in this section.

Table 25.1: Dry lease prices for different contract durations

Contract duration	Annuity (USD)	Dry lease price (USD/hr)
15 years	$ 20 240	$ 40.48
10 years	$ 26 670	$ 53.15
8 years	$ 31 420	$ 62.84

The design life cycle of the aircraft is 15 years. As such, there is one contract that comprises the full design lifetime of the aircraft. This is the cheapest contract, since the payment of the aircraft is spread over 15 years.

Since customers might not want to be bound to a contract for 15 years, an extra clause will be added to quit the contract prematurely, provided that the lessee is able to find a new user for the aircraft and the lessor approves this new user, based on the liquidity of the user. This is analogous to the normal reselling of an aircraft. Next to that, three more contract forms are provided, for a shorter leasing duration. First two of them will be explained. These are the 8- and 10-year contracts. These contracts are slightly more expensive, but give the customer more flexibility, which is an advantage in difficult economic times. At the end of these contracts, the aircraft is fully paid off but it is not yet at its end-of-life. The original customer can then either decide to renew the contract for a much lower price for a few more years or can return the aircraft to the manufacturer. The manufacturer can then find a new customer to lease the aircraft for a low price or can, when no customer are found, decide to recycle the aircraft.

Finally, the most flexible option is the 2-year contract. After two years, only a quarter of the airplane has been paid off. This means that three more contracts are needed for the manufacturer to gain profit. A pitfall is that a new lessee needs to be found every two years. However, since the lease price after the first 2-years contract is already lower (see table 25.2), it is likely that there is a market for used aircraft under a lease construction. The hourly dry lease prices again have been calculated for 500 annual flying hours.

Table 25.2: Dry lease prices for consecutive 2-year contracts

Contract	Annuity (USD)	Dry lease price (USD/hr)
First contract (year 1-2)	$ 33 950	$ 67.90
Second contract (year 3-4)	$ 32 500	$ 65.00
Third contract (year 5-6)	$ 31 100	$ 62.20
Fourth contract (year 7-8)	$ 30 210	$ 60.42

Chapter 26 | Operational Costs

The operational costs of the Cradle to Cradle® aircraft are separated into several variable costs, as general maintenance, overhaul costs, fuel costs and fixed costs, including parking and insurance. These eventually are the building blocks for the total operational cost, wet lease price and total cost of ownership. The costs described in this chapter are again based on 500 flight hours per year.

General Maintenance: The first aspect of labour comprises of the costs involved with disassembling, changing and assembling parts for maintenance. This is estimated to be $ 7 per flight hour on average. The parts required for this maintenance, cost around $ 9.20 per hour. Lubricants, filters & cooling fluids will add to a total of $ 2.50 per flight hour. The last expense is the periodic inspection. There are two type of inspections, one every 250 flight hours and another one every 1 100 flight hours. The cost of these inspections are $ 12.50 per hour [126]. These cost are summarised in table 26.1.

Table 26.1: General maintenance cost per flight hour

	Cost per flight hour
Maintenance - Labour	$ 7.00
Maintenance - Parts (Avionics and Mechanical)	$ 9.20
Lubricants, Filter & Cooling fluids	$ 2.50
Periodic inspections (250 and 1 100 hours)	$ 12.50
Total general maintenance cost	**$ 31.20**

Overhaul Costs: An engine overhaul needs to be performed after 2 000 flight hours. The costs for this overhaul are estimated to be $ 10 000. These costs are based on the replacement of the entire engine (around $ 14 000) and the sale of the old one for an amount of $ 4 000. For a propeller, the time before overhaul is 2400 flight hours. The cost of a new wooden propeller is $ 1 450. These data can be converted into a dollar per flight hour price of $ 5.60.

Fuel Costs: The fuel cost is dependent on the fuel price and the fuel usage of the engine. The fuel price of E100 was found to be around $ 1.00 (chapter 13). The fuel flow of the engine is 25.5 litre per hour (chapter 15). Combining these parameters leads to a price of $ 25.50 per flight hour.

Fixed Costs: The above described costs are mainly determined by the amount of flight hours. There are however also costs that are purely related to the aircraft. These are the hangar (parking) cost and aircraft insurance. The parking cost are retrieved from the tariffs of Rotterdam The Hague Airport [127]. The yearly cost is again distributed over the amount of flight hours, leading to $ 12.16 per flight hour. The insurance costs are based on a Cessna 172 for a student certification class (calculation from Aircraft Owners and Pilots Association; AOPA [128]). The insurance cost per flight hour is $ 2.90. The fixed cost adds up to a total of $ 15.06.

Total Operational Costs: The total operating costs are all the variable costs associated with operating the aircraft on an hourly basis during cruise flight included distributed fixed costs. The variable costs comprise of the before mentioned maintenance, fuel and overhaul costs. The fixed costs are parking and insurance costs and are distributed over the hours flown per year. Here the total operational costs add up to: $ 77.37 per hour.

Wet Lease Price: The wet lease price is based on a dry lease PLUS approach. This is the dry lease price plus the general maintenance cost, overhaul costs and insurance. Fuel and parking are not included in the wet lease price. For an 8, 10 and 15 year lease contract, this is respectively an hourly rate of $ 102.54, $ 92.85 and $ 80.18.

Total Cost of Ownership: The total cost of ownership is the cost that an owner on average would spend on his aircraft per flight hour. This is constructed with the dry-lease price, total operational cost and an assumption on the landing fees. The landing fees are assumed to be paid 250 times per year based on 500 flight hours. Which means an average flight time of 2 hours. The total cost of ownership for a 8, 10 and 15 year contract would respectively be $ 152.41, $ 142.72 and $ 130.05 per flight hour.

Chapter 27 | Supply Chain and Maintenance Management

Aside from determining the dry and wet lease price of the InfiniCraft, it must be decided where and by who the aircraft will be assembled and disassembled. The above mentioned question will be answered in this chapter through a supply chain analysis. The supply chain management described in this chapter is a general case, which means that it can be applied on a continental scale or global scale.
In the first section of this chapter it will be explained where and by who the InfiniCraft will be built. The second section will elaborate further on the disassembly of the aircraft.

27.1 Aircraft Assembly

From the requirements (as defined in chapter 3) it is known that initially only 500 InfiniCraft will be build. Therefore only one production plant will be built to make those 500 aircraft. The production plant is visualised in the centre of figure 27.6. The main reason for building only one production plant is because a production plant is a fixed cost, independent of the amount of aircraft that are built. In order to reduce the fixed cost per unit, for a given amount of aircraft to be built, the fixed costs must be kept as low as possible.
The fuselage (figure 27.1), wing (figure 27.2), wing strut (figure 27.3) and propeller (figure 27.4) of the InfiniCraft will be built separately in the production plant and transported to the maintenance centres. The final assembly will take place in the maintenance centres.

Figure 27.1: Fuselage of the InfiniCraft when leaving the production plant

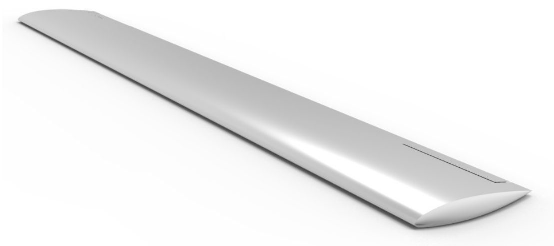

Figure 27.2: Wing of the InfiniCraft when leaving the production plant

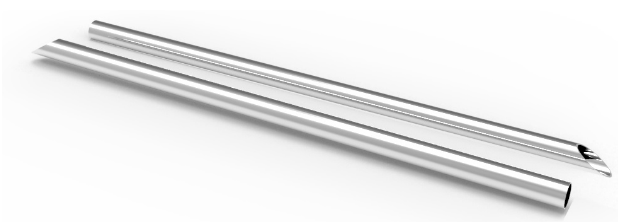

Figure 27.3: Struts of the InfiniCraft when leaving the production plant

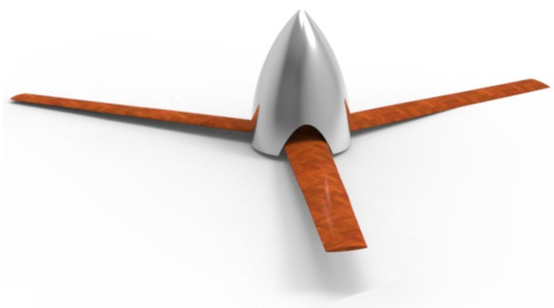

Figure 27.4: Propeller of the InfiniCraft when leaving the production plant

A proper location for the production plant is very important to maintain efficient logistic lines. The following has to be taken into account when defining the location of the Cradle to Cradle® aircraft production plant:

- The constraints set during the unit cost calculations
- Transportation facilities
- Demand for general aviation aircraft in the defined market, which might be global or continental as explained in the introduction of this chapter

27.2 Aircraft Disassembly

In the option tree, displayed in figure 27.5, it can be seen that in total four different options exist to disassemble the aircraft. In order to select one option from the option tree, two small trade-off's have to be made:

- First trade-off: Who will disassemble the old InfiniCraft?
- Second trade-off: Where will the aircraft be disassembled?

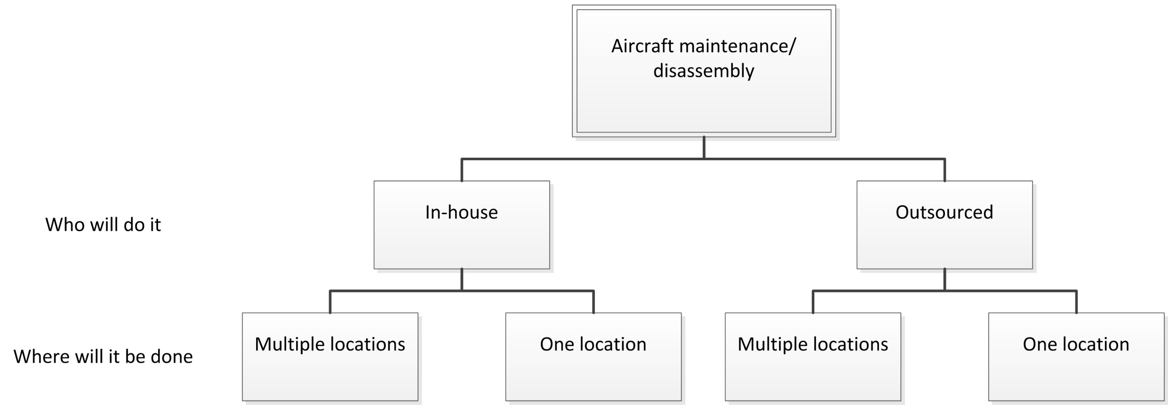

Figure 27.5: Disassembly and maintenance option tree

In the remainder of this section the first and second trade-off will be executed.

27.2.1 First Trade-off

First, a decision is made on who will disassemble the aircraft.
Table 27.1 shows the corresponding trade-off table. In the trade-off table, three trade-off criteria are defined: economical risk, profit and controllability. Each of the two options were graded with high, medium or low for each of the trade-off criteria.

Table 27.1: First trade-off

Criterion	**Self**	**Outsource**
Economical risk	High	Low
Profit	High	Low
Controllability	High	Low

Disassembling the used InfiniCraft ourselves will result in more profit and the disassembly process will be more controllable since it is easier to control your own employees over another company. Aside form these two advantages of in-house disassembly of the InfiniCraft aircraft there is also a major drawback. In-house disassembly will result into more economical risk for the company. This is mainly because the young company will have to focus on both assembly and disassembly of the aircraft, which might reduce the focus on building a Cradle to Cradle® aircraft and eventually the vision statement might not be reached.
Therefore the decision is made to outsource the disassembly of the old InfiniCraft. In order to make sure that the subcontractors are working in a Cradle to Cradle® way, each of the subcontractors will have to pass a certification process which will be set up by the company. During the certification process the subcontractor will need to prove that:

- The subcontractors follow the end-of-life plan as explained in chapter 24.
- The subcontractors follow the Cradle to Cradle® philosophy as explained in chapter 2.
- The subcontractors follow the supply chain as explained in this chapter and visualised in figure 27.6.

As already mentioned in the end-of-life plan, described in chapter 24, some of the parts such as the control surfaces, propeller blades and instruments will not have reached their EOL when the InfiniCraft enters the workshop of the subcontractors to be disassembled. Those parts will be shipped to the production plant to be installed on new InfiniCraft or sent to the maintenance centres. The subcontractor who will disassemble the InfiniCraft will also receive damaged or broken parts from the maintenance centres.

27.2.2 Second Trade-off

Now that is is known that the disassembly of the aircraft will be outsourced to subcontractors, it must be determined whether the aircraft will be disassembled by one or by multiple subcontractors.
In order to reduce the transportation cost, time and waste of ethanol fuel to fly the aircraft from its home base to the place where it will be disassembled, dotted line in figure 27.6, multiple subcontractors will be identified on each continent.

27.3 Aircraft Maintenance

In the option tree displayed in figure 27.5, it can be seen that there are again in total four different options for maintaining the aircraft. In order to select one option from the option tree, two trade-offs have to be made:

- First trade-off: who will maintain the InfiniCraft?
- Second trade-off: where will the InfiniCraft be maintained?

It must be noted that the outcome of the trade-offs will strongly be influenced by the supply chain management defined in this chapter.

27.3.1 First Trade-off

For the same reason as out-sourcing the disassembly of the InfiniCraft, also the maintenance of the aircraft will be out-sourced. In order to make sure that the subcontractors are working in a Cradle to Cradle® way, each of the subcontractors will have to pass a certification process set up by our company. The certification process to become a maintenance centre will be more strict than the certification process to disassemble the old InfiniCraft. This has two reasons:

- The maintenance centres will represent the company.
- The maintenance centres will be responsible for the final assembly of the InfiniCraft.

27.3.2 Second Trade-off

Once it is known that the maintenance of the aircraft will be outsourced to subcontractors it must be known if the aircraft will be disassembled by one subcontractor or by multiple subcontractors.
For the same reason as identifying multiple subcontractors to disassemble the InfiniCraft also multiple maintenance centres will be identified. Since the maintenance centres and the subcontractor who will disassemble the aircraft will have to work together in a close relation they will be located close to each other.

27.4 Supply Chain and Maintenance Plan

In figure 27.6, the complete supply chain and maintenance plan is displayed.

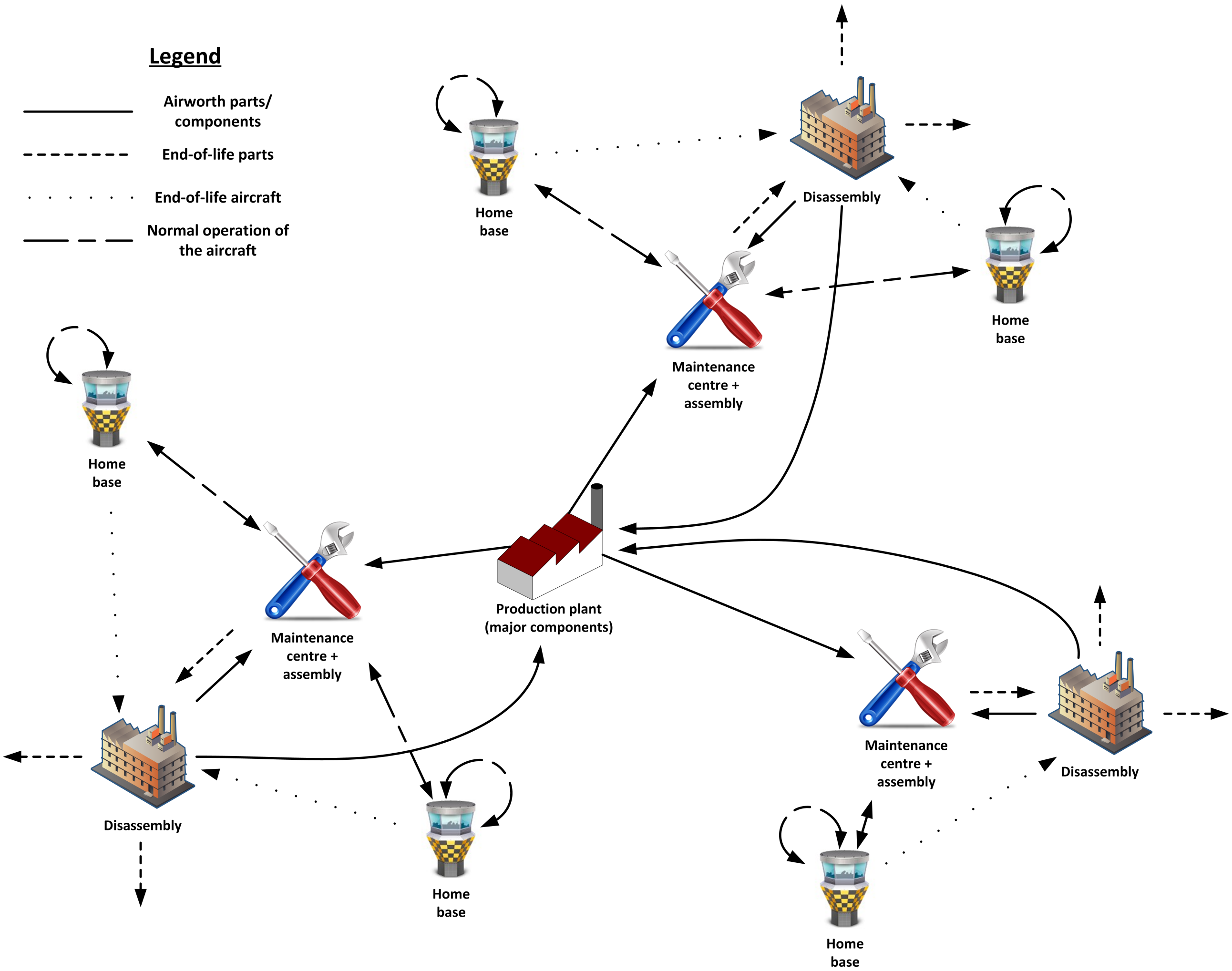

Figure 27.6: Visualisation of the supply chain management and maintenance management

PART VI

CONCLUSION

"The Stone Age did not end because humans ran out of stones. It ended because it was time for a re-think about how we live."

William McDonough,

Co-author of the book *Cradle to Cradle: Remaking the Way We Make Things*

Chapter 28 | Verification and Validation

Verification answers the question: "Is the product designed in the right way?". This process will be done by assessing whether all the requirements have been met by the design, and how this assessment should be done. The purpose of validation is to answer the question: "Does the product do what it was intended to do?" Validation procedures proof that the design accomplishes the intended purpose based on stakeholder expectations [13].

28.1 Verification

For the verification of the design, four main methods exist:
1. Inspection of the documentation or the product itself
2. Mathematical or other analysis techniques
3. Demonstration through operation
4. Test under representative conditions

In this phase of the design, the first two methods can be used to verify the design. The latter two require test-aircraft. In the following paragraphs each of the requirements from chapter 3 is discussed and it will be verified whether the requirement has been met so far.

28.1.1 Requirements Verification

Design requirements

- *The unit cost shall not exceed $ 150 000*
  This requirement has not been met, the InfiniCraft has a unit cost of $ 179 530. Already very early in the design process it became clear that an initial cost overshoot was likely due to changes to the materials and fuel source. It should be noted however that although initial costs may be higher, the operational costs are significantly lower due to smart design. This compensates for the higher unit costs, resulting in a competitive aircraft. Nevertheless the total cost of ownership of the InfiniCraft is very low.
- ✓ *A total of 500 aircraft units shall be produced*
  This requirement cannot be verified yet, since it is not known how many aircraft will exactly be produced. Throughout the report, a production of 500 units has been assumed however, so it is certainly achievable.
- ✓ *The aircraft shall be able to carry a total number of two passengers including the pilot*
  This requirement has been met. The aircraft has been designed for a payload capacity of 181 kg, which is enough for two persons plus their baggage.
- ✓ *The aircraft shall be on the market in 2025*
  Although verifiable at this moment, the design of the InfiniCraft was made with this requirement in mind. All used technology was therefore chosen on its availability in 2025. It can therefore be concluded that this requirement has been met, and that the InfiniCraft will very certain fly in 2025.
- *The aircraft shall have a minimum life span of 30 years*
  As explained in chapter 3, the lifetime has been halved to compensate for the reduced mechanical properties of Al-6022, a much better recyclable alloy than currently used alloys. The design lifetime of the InfiniCraft is thus 15 years. Nevertheless 93,4 % of the InfiniCraft's OEW is recycled.
- *The aircraft shall be designed for 20 000 flight hours*
  Idem to the previous item, the aircraft has been designed for 10 000 flight hours.
- *The aircraft shall be designed for a total number of 12 000 flights*
  Idem to the previous item, the aircraft has been designed for 6 000 flights.

Mission requirements

- ✓ *The aircraft shall have a range of 1 000 km*
  The aircraft has been designed for a range of 1 000 km. From the payload weight-range diagram in chapter 13 it can be seen that this requirement has been met with maximum payload.
- *The aircraft shall have a cruising speed of 200 km/h*
  The cruising speed has not been directly used in the design process. The structural sizing has however been

performed based on a cruising speed of 200 km/h. It needs further investigation and an aerodynamic analysis to verify that this requirement has been met.

- *The cruise altitude shall be 3 050 m*
  Idem to the previous item, the cruising performance of the aircraft has not been analysed intensively. However, again, as the design is not far off from reference aircraft, it is safe to assume that this requirement has been met. Further investigation is however required to verify the design for this requirement.
- ✓ *The maximum take-off length shall be 500 m (on tarmac runways)*
  In the initial sizing of the aircraft, the InfiniCraft has been sized for a take-off length of 500 m. For now this requirement is as such met.

Cradle to Cradle® requirements

- ✓ *The aircraft shall be designed according to the Cradle to Cradle® principles [9]*
  - ✓ *At least 90% of the OEW shall be fully recyclable at the aircraft's end-of-life*
    In chapter 24 it has been found that 93% of the aircraft's OEW can be recycled. This requirement has thus been met.
  - ✓ *Recycled materials shall be re-integrated through either the technical cycle or the biological cycle, according to the Cradle to Cradle® principles*
    89% of the aircraft's OEW is upcycled. A huge amount of recycled materials are therefore re-integrated while remaining their qualities.
  - ✓ *A disposal plan for end-of-life shall be provided* A disposal plan is provided in chapter 24. The requirement has thus been met.
- ✓ *The aircraft shall be able to operate according to the Cradle to Cradle® principles*
  - ✓ *The aircraft shall have a carbon emission of no more than 50 kg/h*
    As mentioned in chapter 29, the carbon emission of the InfiniCraft is about 39 kg/h. This requirement has thus been met. When taking the life cycle analysis of chapter 14 into account, the effective carbon emission can nearly be reduced to zero, since the InfiniCraft is effectively carbon neutral.
  - ✓ *Current solar energy shall be used as an energy source for the aircraft*
    With the use of bio-ethanol from crops and waste, current solar energy is used to propel the aircraft. This requirement has thus been met.

Additional requirements

- ✓ *The noise level shall not exceed 62 dB, measured according to the FAR Part 36 regulations*
  From chapter 16 the estimated noise of the InfiniCraft is 60.4 dB. The requirement has thus been met.
- ✓ *An in-flight emergency solution shall be provided*
  In chapter 17 several emergency solutions have been discussed. The standard emergency equipment is implemented in the aircraft. Two additional in-flight solutions were discussed, which can be implemented in the InfiniCraft. It can thus be said that this requirement will be met.

28.1.2 Certification

As a final step in the verification process, the InfiniCraft is checked with the CS-23 certification [10]. As a full certification of the aircraft is beyond the scope of this design process, only the key certification requirements have been used for the initial design. For this reason, the basic certification requirements regarding the weight, flight envelope and stability and control have been considered. It can thus be concluded that the InfiniCraft at this stage complies with the key certification requirements but needs further investigation in order to fully certify the aircraft. It should also be noted that the Al-6022 alloy should be certified before further analysis can be performed.

28.2 Validation

After verifying the requirements, the final step is to validate the design. As mentioned above, the validation process is needed to proof that the design accomplishes the intended purpose. Looking at the stated intentions of the design in chapter 1, the design has to inspire others to create and use self-sustaining aircraft, based on the Cradle to Cradle® philosophy. The design has to be competitive and lay the basis for an aviation industry in which aircraft are manufactured and operated without any negative impact on future generations.

By implementing automotive aluminium alloys in the design, the market for recycling is significantly increased. Also, by making use of rivets from an identical alloy, down-cycling of the aluminium is prevented. If materials

for the interior parts and secondary structure are then carefully chosen, waste can be reduced up to 7% of the OEW. Combined with the use of current solar income through biofuel, an effective Cradle to Cradle® design is accomplished which inspires to bring back the waste percentage even more, and to develop sustainable alternatives to fossil fuels. It is important to realise however, that this will only work when the InfiniCraft is competitive. Although the unit cost requirement has not been met, the InfiniCraft still proves to be competitive due to its low operational costs, combined with a lease structure.
It can be concluded that although a lot of the validation process can only be finished once a prototype is flying, the InfiniCraft fulfils its intended purpose, and is capable of inspiring the aerospace industry to eliminate waste, and to come up with environmental friendly solutions to problems as the depletion of resources.

The InfiniCraft, an inspiration for future generations:

Figure 28.1: The InfiniCraft

Chapter 29 | Comparison InfiniCraft and Cessna 162

During the design of the InfiniCraft, the Cessna 162 has been used as reference aircraft. Therefore a comparison between the InfiniCraft and the Cessna 162 can show the relevance of a Cradle to Cradle® design. As can be seen in table 29.1, just like the Cessna 162, the InfiniCraft is a two-seater general aviation aircraft with a high-wing configuration. The InfiniCraft is able to fly 285 km further, this translates to a difference between MTOW and OEW for the InfiniCraft and Cessna of 322 kg and 217 kg, respectively. Also the lower energy density and higher energy consumption of ethanol compared to avgas lead to a higher fuel weight, which is a second factor for the difference between MTOW and OEW.

Furthermore, the fuel consumption of the InfiniCraft is 4.68 L/hr higher. This is due to the higher weight, but also lower energy density, where a higher fuel flow is needed. The energy consumption shows the weight impact, as the efficiencies of both engines is calculated to be approximately 40 %, based on MATLAB® calculations.
The InfiniCraft has 7.07 kg/hr lower CO_2 exhaust emissions, where the LCA emissions are even lower as seen in the LCA analysis in chapter 14. This is due to the fact that CO_2 is absorbed by the plants, while only transport and process related emissions count for the final LCA emissions, contrary to fossil fuels where the real emissions plus transport and process emissions count as the LCA emissions.

Due to the higher initial cost, the lease price of the Cessna will be approximately $ 13 /hr lower. However the total cost of ownership is $ 7 /hr lower for the InfiniCraft. This can be mainly explained by the difference in fuel cost for ethanol and avgas, where ethanol is cheaper per MJ.

Furthermore the primary structure of the InfiniCraft is made from one aluminium alloy according to the Cradle to Cradle® philosophy, whereas the Cessna 162 has a mix of aluminium alloys and different metals, which are fairly difficult to recycle and time consuming to separate at disassembly. The secondary structure of the InfiniCraft is made from thermoplastic composites, which are recyclable, where the carbon fiber of the Cessna 162 will contribute mainly to waste. The structure of the InfiniCraft has more welds at strategic places, where bolts are used at bonds which separate parts that need to be disassembled, compared to the focus of easy assembling of the Cessna 162. Last the rivets of the InfiniCraft are made from the same material as the plates, which eliminates the need of drilling out the holes at disassembly.

The InfiniCraft and Cessna are therefore in many aspects very similar, however when it comes to recyclability and total cost of ownership the InfiniCraft has its major advantages.

Table 29.1: Comparison InfiniCraft and Cessna 162

Parameters	**InfiniCraft**	**Cessna 162**
Passengers	2	2
Range [km]	1 000	815
Engine power [hp]	103	100
Take-off length [m]	500	347
Maximum climb rate [m/s]	5	4.5
OEW [kg]	407	382
MTOW [kg]	729	599
Fuel consumption cruise [L/hr]	25.5	20.8
Energy consumption [MJ/hr]	765	658
CO2 emission exhaust [kg/hr]	38.7	45.8
Cost price 10 year [$]	179 530	149 900
Dry lease price [$/hr]	53.15	39.67
Wet lease price [$/hr]	92.85	79.47
Total cost of ownership [$/hr]	142.72	149.48
Primary structure	Al-6022	Aluminium alloy materials
Secondary structure	Thermoplastic composites	Carbon fibre
Joining	Friction stir welding, bolts and rivets	Standard welding, bolts and rivets

Chapter 30 | Impact on Society of the InfiniCraft

The whole Cradle to Cradle® aircraft design project has been executed in order to contribute to an environmental-friendly general aviation industry, having a positive impact on the society. At the end of the preliminary design phase of the InfiniCraft, it is important to identify the main drivers of its eco-friendly design. From chapter 1, four key impacts on society have been identified. This chapter will explain how exactly each one of those impacts has been achieved within the design of the InfiniCraft.

30.1 Inspire Other Manufacturers

The inspiration of current manufacturers started with the identification of the Cessna Skycatcher as reference aircraft. By doing so, several important design parameters and aircraft characteristics stayed conventional such as the wing-, empennage- and engine configuration. This allowed the project to focus especially on key contributors towards Cradle to Cradle® aircraft design while demonstrating the implementation of the Cradle to Cradle® philosophy within current aircraft.

Today's general aviation manufacturers take no incentive at all to put a decent end-of-life plan in place for their aircraft. Instead, they focus on creating long life, reliable aircraft without any thorough assessment of their ecological impact. The reason for this is the lack of profitability of end-of-life operations on today's aircraft and the limited directly added value of an eco-friendly design towards customers.
What they do not know however is the fact that only minor updates are required on today's aircraft to achieve enormous ecological enhancements. The current Cradle to Cradle® design has demonstrated both good and profitable end-of-life possibilities of aircraft by only implementing minor updates to current aircraft, such as improved joining methods and smarter material selection. The only major consequences for the aircraft's performance is a 7 % weight increase, compared to the Cessna Skycatcher.

30.2 Reduce Ecological Impact

The main principle of the Cradle to Cradle® philosophy is to eliminate the environmental impact of products. The current design contributes to this goal in several ways. Using recycled material instead of primary material reduces energy consumption, exploitation area for the raw materials and landfill at the end of its operational life. Using recycled aluminium for example for the aircraft's structure results in 95 % energy savings and avoidance of the exploitation of new bauxite ore. The implementation of the Cradle to Cradle® philosophy will stop the growth of aircraft graveyards and stop the use of limited resources.

The biofuel engine used for the propulsion system allows the InfiniCraft to reduce its CO_2 footprint by 75 % compared to regular gasoline engines. The generation of the bio-ethanol also influences positively the near-airport society as ethanol can reduce local waste streams.

30.3 Economical Benefits

The aviation industry is known for its good international collaboration. For this reason, the development and operations of a InfiniCraft is inevitable much more globally positioned, compared to other Cradle to Cradle® projects. Therefore, the InfiniCraft will contribute to a worldwide collaboration in the field of eco-design.

Even though the InfiniCraft's production cost is approximately 20 % higher compared to the Cessna Skycatcher, impact cost on future society has not been taken into account. Today's aircraft are lacking end-of-life management, resulting in a full transfer of responsibility of those waste streams towards future generations. One has to realise that there will be a moment at which society will have to tackle those waste management problems created before, resulting in disastrous economical impacts. The current design guarantees an influence-free concept, leaving no trail for future generations and their environmental situation.

With the InfiniCraft, overall demand for bio-ethanol will increase, which will boost the industry. Better techniques with higher efficiencies will be developed and new, more optimal crops will be used, which have an even lower impact on human beings. Therefore, the average cost of bio-ethanol will decrease again, implying new industries to be interested in the use of bio-ethanol again, increasing again the overall demand. This is a perfect example of the economies of scope, which provides the InfiniCraft with high potential in different sectors, as the example of bio-ethanol could also be applied to other sectors such as the aluminium recycling industry.

30.4 Change in Mindset

Modern society is typically defined as an ownership culture, in which people become the owner of goods when paying for them. Once those products enter their end-of-life phase, people dispose their goods as pure waste without any interest in the environmental impact of their acts. The strive of the current design is to change society's mindset from an ownership culture towards an operator culture. By implementing a leasing concept, the pilot's role in the aircraft's operational use changes from being the owner of the aircraft to its operator. By doing so, the end-of-life responsibility of the aircraft stays at the manufacturers side, safeguarding its recycling process according to the Cradle to Cradle® principle.
The current design has also introduced a new vision towards a product's life cycle. The typical production, usage and disposal mentality of product users today has been replaced by an approach in which current products will be updated repeatedly according to society's trends, avoiding any disposal and making the 'conceptual' life span of the aircraft infinite.

Even though the implementation of the Cradle to Cradle® philosophy throughout the aircraft's life cycle remains the responsibility of the manufacturer, the project also wants to add consciousness to modern society. Current aircraft have important limitations towards the Cradle to Cradle® philosophy, such as fossil fuel dependence and expensive end-of-life solutions. By stressing those limitations numerous times, the project has tried to highlight the importance of eco-friendly and Cradle to Cradle® aircraft design. Those limitations have been identified early in the design phase, resulting in an elimination of them in the InfiniCraft.

Chapter 31 | Future Approach

Up to now, the aircraft has been designed to be able to fly in 2025. However, as technologies develop, new solutions may become available in the near future. This chapter provides a sensitivity analysis on the possible changes that could be made to the design and finally a roadmap to a fully Cradle to Cradle® design is presented.

31.1 Sensitivity Analysis

Future developments may provide alternative solutions for the design. It is important to assess the impact that these developments will have on the aircraft design and on its impact on the environment. This section will provide a list of possible design changes together with their impact on the design.

31.1.1 Hydrogen as propulsion system

As Shell is expecting that hydrogen as energy carrier will get a boost in the near future [129], and ethanol prices might rise significantly in the near future due to public dissatisfaction, the case should be considered that the fuel system of the design would change to a hydrogen based system. From section 7.2, the system parameter ratios between biofuel and hydrogen were determined. These are listed below in table 31.1 to present a representation of the impact that a hydrogen propulsion system would have on the design.

Table 31.1: Propulsion system comparison

Parameter	Ratio
System weight	+35 %
System Price	+35 %
Fuel price	−30 %
Land use	−100 %

It can be seen that although the system price and weight will increase, the fuel price and land use (or environmental impact) are greatly reduced. It should be noted that when developments on hydrogen continue, lighter systems may become available, providing an excellent alternative to a biofuel based propulsion system.

31.1.2 Composite Structure

Today, more and more aircraft have composite structures integrated in their design. While having enormous advantages regarding weight savings, composites usually yield high cost prices. However, as composites are getting developed, these costs can be reduced.

The most important aspect to concern however is the ecological impact of composites. Recycling of composites proves to be difficult as they often are made out of two different materials. Furthermore, if long or continuous fibers are used, their quality decreases after the recycling process. Together with changing joining methods, maintenance steps and a disassembly plan, the change to a composite structure proves to be a challenge with respect to the Cradle to Cradle® philosophy.

31.1.3 Compression Moulding of Secondary Structures

The InfiniCraft relies on the availability of 3D printers at maintenance centers which are capable of printing secondary structures. Although being a feasible alternative to current production methods of thermoplastic composite structures, there should be an answer to the case where 3D printing is not capable or allowed to print the required secondary structures. In this case, compression moulding should be used for the production of the structures. This technique, frequently used nowadays, is a good alternative to produce and maintain the TPC structures. The major disadvantage is that this cannot be done locally due to the required infrastructure.

31.1.4 Electronic Fuel Injection

The current engine relies on a carborator to blend the air and fuel in order to function. An alternative to the carborator is an electronic fuel injection system which is much more efficient in use. It does however imply more costs and weight, up to an additional cost of \$10 000 and a weight increase of 10 kg.

31.1.5 Fly-by-wire

Commercial aircraft nowadays mostly make use of a fly-by-wire control system. This system replaces the cables and rods with electronic wiring which send the control input to the control surfaces, which are powered either by electronic or hydraulic actuators. Reducing the weight enormously, and simplifying the control signal transportation, the fly-by-wire system does bring more complexity in the design, such as more advanced computer systems and actuators. When integrating this system in the future, it should be possible to disable the digitally bounded flight envelope in order to enable the student to perform all the required manoeuvres.

31.1.6 Extensive Emergency Solution

Currently, a lot of effort is put into making aircraft safer in case of an emergency. An example of a emergency solution is the ballistic recovery system (BRS), developed by BRS Aerospace [57]. To further enhance the safety of the InfiniCraft, this BRS system could be implemented in the design. This implementation would however result in increased costs and increased weight, due to the increase in structural weight to cope with the additional forces when the parachute deploys.

A much cheaper and lighter, but less safe, solution can be found in implementing airbags into the cockpit that can be deployed in crashes or emergency landings. Although it is a minor safety improvement, it proves to be an effective and reliable system which does not require a significant increase in structural strength and does not result in problematic increased weight and costs.

31.1.7 Ecological regulations

The environmental impact of products is becoming a major importance in its design. In the automotive industry, certifications are already implemented. With the growing awareness of climate change it is likely that regulations on ecological impact will become more stringent. When this happens, this would mean a major competitive advantage for the InfiniCraft. This might lead to the following paragraph which is an increase of the production number.

31.1.8 Production Numbers Increase

In case the InfiniCraft becomes such a success that production numbers can increase, this will have an huge impact on the business case. As the fixed costs will be spread among a larger number of aircraft, they will decrease per aircraft, hence decreasing unit costs. Also due to the outsourced production, more jobs will be created, improving local economies. Much attention should however be paid to logistics. As more aircraft will be leased, the risk of loosing materials or equipment becomes much higher. By creating a more dense maintenance system (e.g. more maintenance centres per area), this problem could be solved.

31.2 Roadmap to Cradle to Cradle®

One does not immediately develop a fully Cradle to Cradle® product. This is achieved through multiple developments. For this reason a roadmap is created for the design to identify the milestones that have to be reached in order to achieve a fully Cradle to Cradle® design. In figure 31.1, the roadmap to the Cradle to Cradle® design is displayed.

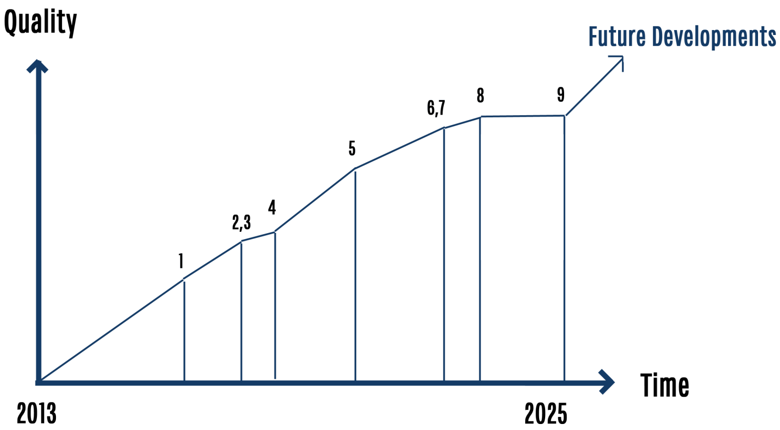

Figure 31.1: Cradle to Cradle® Roadmap

Below, each of the milestones are described in more detail:

1. **Aluminium Al-6022 certified for aviation:** The aluminium alloy that is used for the InfiniCraft is nowadays used in the automotive industry. Many properties of the alloy are already known from the automotive industry, but properties on fatigue life and other aerospace related parameters are still to be investigated. This will require testing and ultimately certification of the alloy for use in the aviation industry.
2. **Fully Cradle to Cradle® coatings become available:** Research is already being done on recyclable coatings for aircraft. For the design of the InfiniCraft it has been assumed that these coatings become available in the coming 12 years.
3. **Recycling of thermoplastic composites is optimised:** For the recycling of the secondary structures, the recycling of thermoplastic composites needs to be improved. It is assumed that the recycling process of thermoplastics will be improved in the coming years.
4. **3D-printing of secondary structures is certified:** More research needs to be performed in the printing of secondary structures of the InfiniCraft. 3D-printing becomes more and more available. A milestone is the certification of 3D-printing for aviation.
5. **Mobile avionics certification:** Although mobile devices are already widely used in the cockpit, they have not been officially certified. As such they cannot replace existing avionics and instruments. A milestone in the future is the certification of these devices, such that they can be used as true avionic systems.
6. **Biofuel becomes available worldwide:** In order to make the InfiniCraft a true competitive aircraft, bio-ethanol needs to become available worldwide.
7. **A Cradle to Cradle® engine is developed:** In the current design of the InfiniCraft, a Rotax engine is used. This engine is however not specially designed for recycling at its end-of-life. Although parts of the engine can already be recycled very well, more research should be done in the full recycling of the engine. A milestone would be the availability of a Cradle to Cradle® engine.
8. **Ethanol production is sustainable:** Ethanol that is currently available on airports is generally not produced in a sustainable way. It is assumed that in the coming 12 years, the production will start to become more and more green. Ultimately a milestone is to have 100% sustainable ethanol.
9. **Maintenance logistics are set up:** The InfiniCraft will use a non-conventional way of maintaining and producing the aircraft. The decentralisation of the maintenance and assembly process requires certified sub-contractors. The realisation of these business-cooperations is the formal milestone for building the InfiniCraft.

Chapter 32 | Conclusion

This report introduced the environmentally-friendly design of a general aviation aircraft according to Cradle to Cradle® principles. The design process, written down in the report, will be concluded in this chapter. Five major parts were discussed in the report: an introduction to the design, the sizing of the aircraft, a power & propulsion analysis, a structural sizing & material selection and an operations & logistics analysis.

The decision was made to make the InfiniCraft fly on biofuel instead of hydrogen. For the aircraft configuration, a high wing design was chosen with a low tail and a tractor propeller. This would ensure a proper focus on a realistic Cradle to Cradle® design of the aircraft which can set an example to other aircraft manufacturers around the world. The primary structure of the aircraft will be made from aluminium while the secondary structures are made from thermoplastic composites.

An initial sizing was done on the InfiniCraft. The following parameters were obtained:

- A wing surface area of 10.4 m
- An aspect ratio of 7
- Plain flaps with a ΔC_L of at least 0.9
- A NACA 2412 airfoil

With these parameters a class I and class II weight estimation were executed. With these calculations the mass of the most important components were estimated, based on statistical data. After the final design was finished, these results were updated with the actual design data, resulting in the following weights:

- The OEW equals 407 kg.
- The payload varies between 0 and 181 kg. The payload includes the pilot, passenger and their luggage.
- The reserve fuel equals to 28 kg.
- The mission fuel to fly 1 000 km equals 113 kg.
- The MTOW equals 730 kg.

Once the weights of the different aircraft components were determined, the longitudinal stability & control of the InfiniCraft was investigated. With the use of loading diagrams, centre of gravity range plots and a scissor plot, it was determined that a tail surface of 0.73 m^2 is required. Furthermore, a wing leading edge location of 2.03 m from the nose was computed.
The second part of the design ended with taking a closer look at the control system of the InfiniCraft. The control surfaces of the Cradle to Cradle® will be connected to the cockpit using cables to improve recyclability. Furthermore, it was decided that the InfiniCraft's avionics will consist of the basic six instruments. An iPad ® will be used for additional flight information.

For the power and propulsion of the InfiniCraft, ethanol was chosen as the fuel source. Ethanol is a sustainable fuel type, relatively cheap and will be available by 2025. Aside from selecting the fuel type, its origin and impact on the environment were investigated as well. This was assessed with a life cycle analysis in which four different sources of ethanol were investigated: ethanol derived form corn, switchgrass, sugarcane or waste. In the end, it was decided that the fuel source depends on the region where the InfiniCraft will fly. Rotax 912 ULS engine was selected since it is cheap, light and produces low levels of noise. Finally, a study on the emergency solutions was performed. The InfiniCraft will be equipped with standard safety measures like the ELT, PLB, fire extinguishers and floating devices. Furthermore, the InfiniCraft will also contain seat belts, airbags and optionally a parachute recovery system to further increase the safety of the pilot an its passengers.

The aircraft's primary structure will be made from aluminium 6022-T4. Its main advantages in comparison to typical aerospace alloys like Al-7075-T6 and Al-2024-T3 are its reduced material cost, better corrosion resistance and its higher scrap value. Since Al-6022 is primarily used in the automotive industry, there is a much larger market for resale of scrap material. The main disadvantages of the Al-6022 alloy are its reduced mechanical properties. A silicium anti-corrosion coating is used, which is not as hazardous for the environment as the current chromate based ones.
A semi-monocoque structure will be used for the structural design of the InfiniCraft. It keeps the structure as lightweight as possible. The InfiniCraft will be joined using friction stir welding, riveting and bolting. The welding technique will be used for the primary structure's attachments which are designed according to the safe life principle.

Bolts and rivets provide much better replacement possibilities and will therefore be used for the modular build-up of the aircraft.
Finally, a stress analysis has been performed on both the fuselage and the wing box to make sure that the chosen alloy, with a design strength of 126 MPa at 48 000 cycles, is able to withstand the stresses during flight. Two load cases were considered at the ultimate load factors of $+6.6\,g$ and $-3.21\,g$. Out of this has been found that a strut would be required to carry part of the loads. Eventually, a combined wing structural weight was obtained of 86 kg, 23 kg heavier than the first estimation. With further optimisation, this weight can be reduced. A similar analysis was then performed on the fuselage from which a total structural weight of 82 kg was obtained, 22 kg lighter than expected. It can therefore be concluded that the Al-6022 alloy proves to be a good alternative to currently used aluminium alloys.

Apart from the aircraft's aluminium primary structure, several other materials are being used for the non-critical parts. The aircraft's windows and doors will be made from polycarbonate. The customer gets the opportunity to choose the interior from a list of Cradle to Cradle®-materials, focussing on locally available materials. The remaining secondary structures are made from short-fibre reinforced thermoplastics. Thanks to the upcoming technology of 3D-printing, fast and easy replacements can be printed at the local maintenance centres.
For the end-of-life phase of the InfiniCraft, a total of 93.4 % of the aircraft's OEW has been identified to be recyclable of which 88.7 % according to the Cradle to Cradle® philosophy. Main contributors to the recycling difficulties are the aircraft's coatings, engine block and rubber.

The last part of the report started with computing the cost of ownership InfiniCraft since a lease construction will be used instead of simply selling the aircraft which is normally the case within general aviation. The duration of the contract can be varied, depending on the customer's wishes and the economical environment. Below, the costs are displayed for three possibilities:

- $ 130.05 per hour for a contract duration of 15 years.
- $ 142.72 per hour for a contract duration of 10 years.
- $ 152.41 per hour for a contract duration of 8 years.

As a comparison the Cessna Skycatcher has a total cost of ownership of $ 149.48 based on a lifespan of 10 years.

Finally, a supply chain and maintenance plan was developed. The major components, the fuselage, propeller, strut and wing will be manufactured in-house in one production plant. The components of the InfiniCraft will then be shipped to different maintenance centres where the aircraft are assembled. The assembly, maintenance and disassembly of the InfiniCraft will be outsourced to certified subcontractors.

In general, the conclusion can be made that it is indeed possible to design an aircraft using Cradle to Cradle®. Although a lot of improvements have to be done and research has to be performed, a feasible aircraft has been designed which is able to be on the market in 2025. For customer's, the InfiniCraft has added value: lower operating costs, lower risk because of leasing construction, less noise, updated avionics and customizable interior design. It should be noted that Cradle to Cradle® design never stops, but serves as a roadmap to a truly sustainable future, where waste is left out of the equation, and truly self-sustaining aircraft can exist. Designing a Cradle to Cradle® aircraft is not about changing what it was intended to do, but about changing its intentions towards its environment.

Aicraft Design Using Cradle to Cradle®: Reality or Utopia?

Reality.

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PART VII

APPENDICES

"Now this is not the end. It is not even the beginning of the end. But it is, perhaps, the end of the beginning."

Winston Churchill,

Prime Minister of the United Kingdom during World War II

Appendix A | Detailed Fuel Life Cycle Analysis

In this appendix, the detailed life cycle analysis of corn, sugarcane, switchgrass and waste based ethanol can be found. The final conclusion can be found in chapter 14.

A.1 Ethanol Made from Corn

Making ethanol from corn is a very popular process, especially in the USA. The process is commonly used and is well known. However, methods are not ideal and can actually give worse results than normal gasoline.

A.1.1 Life Cycle

The process that is described in this section is the old process for making ethanol from corn. The whole process can be found in figure A.1.

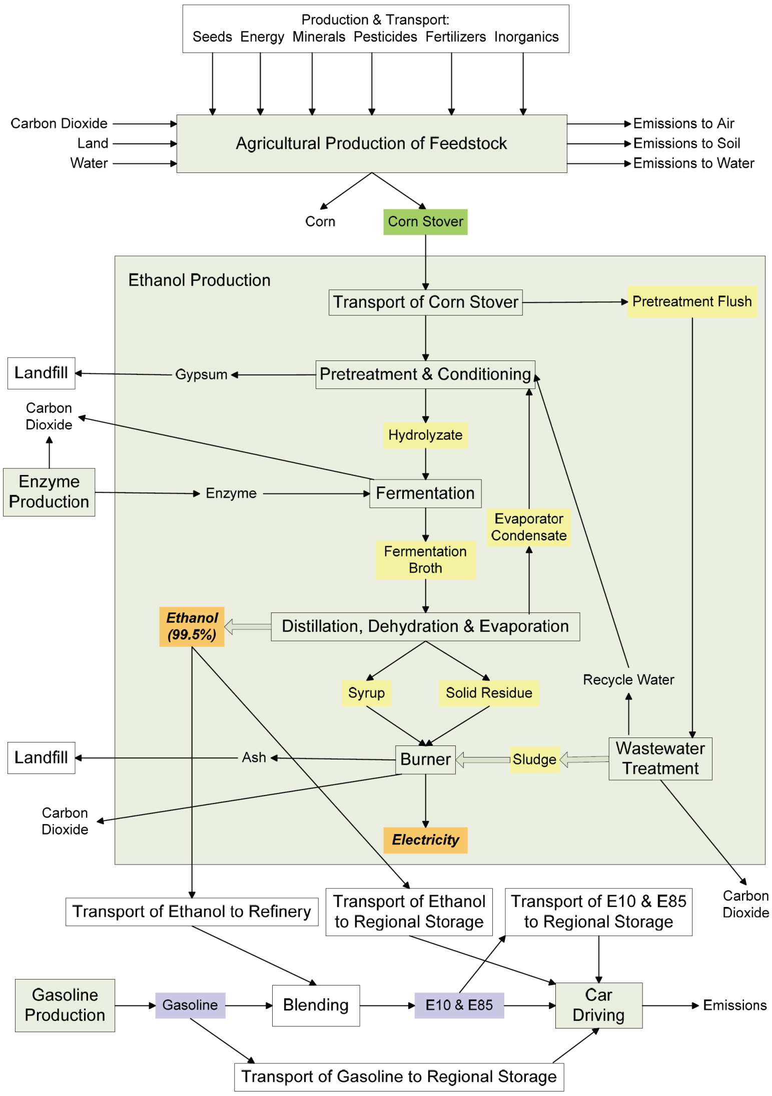

Figure A.1: Life cycle of corn [31]

It can be seen the ethanol is made from a mixture of corn and corn stover. Corn stover is the waste that is left after the corn is harvested. Currently the ratio between corn stover and corn is 1:1. The corn stover is fermented, which is a natural process, but some enzymes are added to this process. After the fermentation, the product is

distilled and the ethanol will be collected and used. The ethanol can than be transported to the refinery. However, the 'blending' does not apply to the Cradle to Cradle® aircraft since pure ethanol, E100, will be used. This makes the 'blending' step superfluous. Only pure ethanol will be used as a fuel for the Cradle to Cradle® aircraft.
After the ethanol is distilled, the waste products can be fed to a burner. In this way, electricity can be produced. This can either be used to sustain the fermentation and distillation process or be sold to the grid.
All these steps in the process of making ethanol will be included in the LCA. Also the transportation, fertilisation, all emissions, etc. All of this will be further discussed in the section environmental impact.

A.1.2 Land Use

In this section there will be investigated how much land there is needed to produce ethanol, based on the current ratio between corn stover and corn and the current available technology. The following facts were found. To produce one gallon of ethanol, 11.84 kg of corn is needed [130]. Converted to metric units, this is 3.2 kg of corn per litre of ethanol. It is also know that on one acre of land (4 047 m^2) approximately 3225 kg of corn can be grown. So for one liter of ethanol, approximately 4.01 m^2 is needed. It has to be stated that approximately half of the corn on this land will be used as food.
This calculation is now extended to the amount of land that is needed to fuel one aircraft for one year. One aircraft can fly 5 hours with 178.5 litres of fuel. On a yearly basis, the aircraft will fly for 500 hours, so 17 850 litres are needed. This means one airplane will need 71 578.5 m^2 per year (if one harvest a year is assumed). As a comparison, this is equal to 15 soccer fields. As can be seen, this is a significant amount of land that needs to be used to make ethanol from corn. However, nowadays the techniques are improving, so in the future this area should go down.
This amount of land is significant because this land can be used for food. Corn only grows on fertile land (in the USA a lot of corn is grown in the midwest, which has a lot of fertile land) so in the end there will be less land for food. This can be a problem in the future, when the world population keeps growing, it might not be smart to use all this land for fuel. This is a big disadvantage of ethanol made from corn. However, new techniques can convert the more of the corn stover into ethanol, which can make this impact less worse.

A.1.3 Environmental Impact

In the thesis written by Lin Luo, a lot of environmental impacts are discussed. In this report, only three of the most important impacts are discussed: the global warming potential (GWP, figure A.2), the toxicity potential (TP, figure A.3) and the ozone layer depletion potential (ODP, figure A.4).

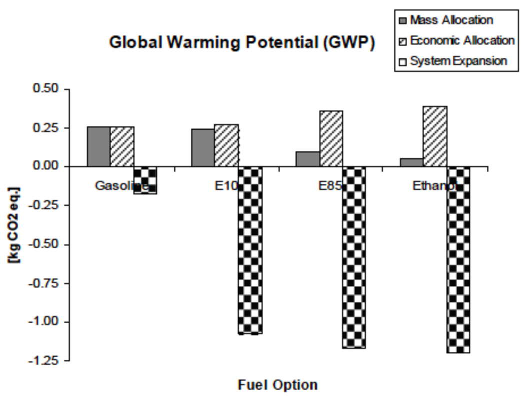

Figure A.2: Global warming potential of corn made ethanol [31]

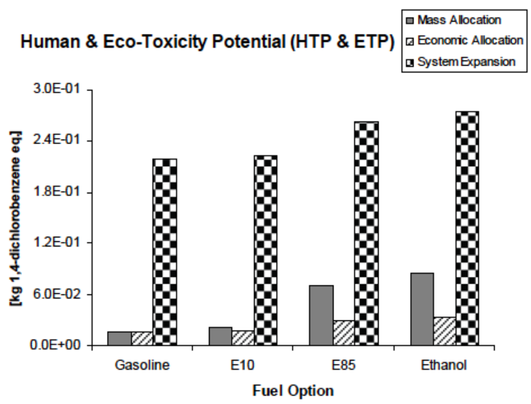

Figure A.3: Toxicity potential of corn made ethanol [31]

The GWP (figure A.2) shows strange results. As can be seen, three different systems are to used to analyse corn based ethanol: mass allocation, economic allocation and system expansion. Mass allocation uses the energy per unit of mass to compare ethanol to gasoline. Economic allocation uses the price per energy to make to comparison while system allocation takes into account the whole life of the corn (from growth of the plant to ethanol). Depending on the method that is used, ethanol can be better or worse than gasoline. It can be seen if mass allocation or system expansion is used, ethanol is doing better than gasoline. This is of course due to the fact that the corn can absorb CO_2 during its growing phase. However, when economic allocation is used, gasoline is better. This is mainly because of the big price difference between corn and corn stover. This shifting is causing the difference with the other methods.

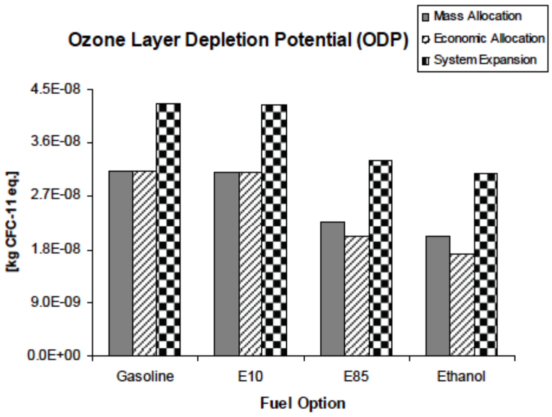

Figure A.4: Ozone layer depletion of corn made ethanol [31]

In figure A.3 it can be seen that the TP of ethanol is worse than the one of gasoline. This is mainly because of all the toxic agrochemicals that are needed to grow the corn. So in this view, gasoline is better for the environment than ethanol.
The last factor is the ODP, which can be seen in figure A.4 and is better for ethanol. This is because crude oil or coal are worse than the agricultural emissions.
In the end, there is no clear conclusion. Depending on what your priorities are, biofuel or gasoline will be better. At the end of this chapter, all the different options will be compared.

A.2 Ethanol Made from Sugarcane

Making ethanol from sugarcane is very popular in Brazil. A lot of sugarcane is grown there, which is the main reason for the fact that Brazil is a big player on the ethanol market. In this section the life cycle, land use and environmental impact will be discussed.

A.2.1 Life Cycle

In figure A.5, a complete overview is given of the life cycle (LC) of ethanol made from sugarcane. It has to be stated that this is the LC of the new process for making ethanol. This new technique uses the bagasse (the waste) of sugarcane. This together with some of the sugar is used and fermented. This makes this process more sustainable than the old process, which just used the sugar.

As can be seen in figure A.5, the whole process starts with the growth of sugarcane. All the necessary products for the growth are accounted for in the LC. The sugar cane is milled after it is ready to harvest. Now some of the juice and the bagasse are used for the fermentation. This product will be distilled and the ethanol is collected. There is also some electricity that is produced. This can be used to sustain the process or can be sold to the grid. Finally the ethanol will be transported and stored before it is used.

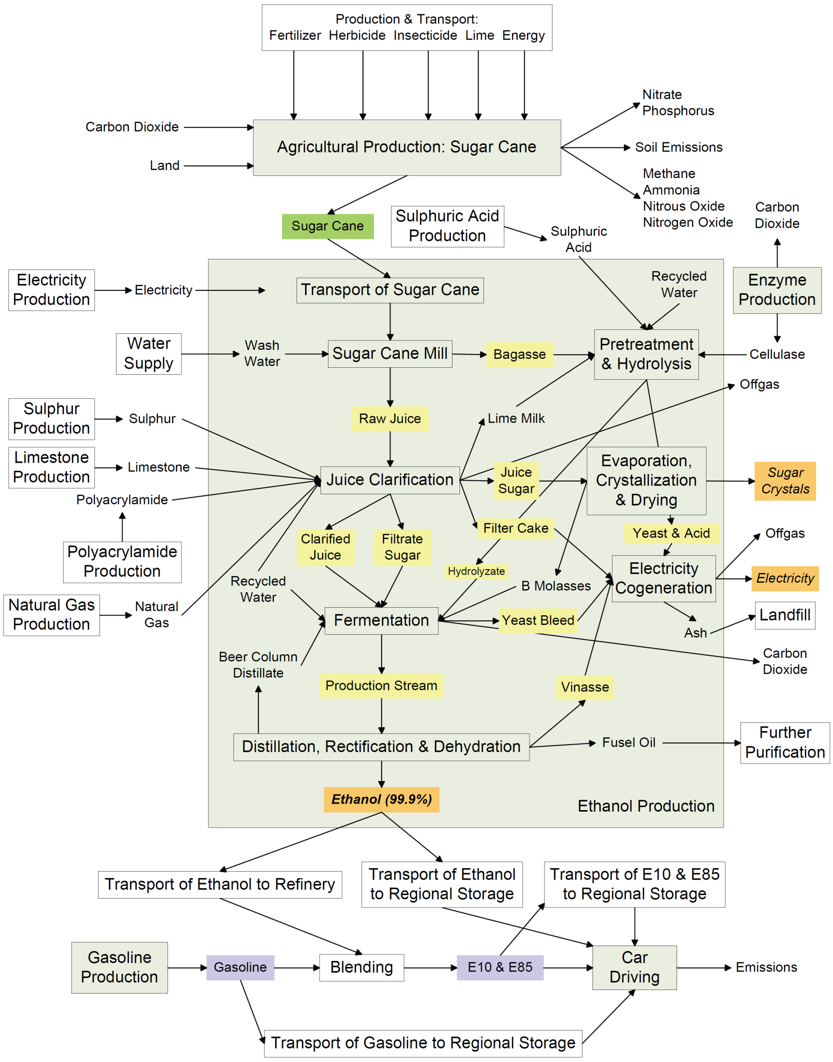

Figure A.5: Life cycle of sugarcane [31]

A.2.2 Land Use

In this section it will be investigated how much land there is needed to produce the ethanol as of today. The following facts were found. On 10 000 m^2, a total of 9 000 litres of ethanol can be extracted from sugarcane [131]. In the near future, this can go up even more. This growth is due to the new techniques that are developed, as explained in the previous section. So for one litre of ethanol, approximately 1.11 m^2 is needed. Of course not all this land is used to produce the ethanol, also sugar is produced.
Based on section A.1.2, this means one airplane will need 19 813.5 m^2 per year (if one harvest a year is assumed). As a comparison, this is equal to 4 soccer fields. As can be seen, this number is lower than the land use for ethanol made from corn.
A final remark here is that when the bagasse is used to make the ethanol and the sugarcane is not especially grown to make ethanol, this is a very sustainable way to make ethanol. The sugarcane can still be used to make sugar, while the waste is used to make ethanol. This is a very efficient and sustainable way of producing ethanol.

A.2.3 Environmental Impact

In the thesis written by Lin Luo, a lot of environmental impacts are discussed. In this report, that would lead to far and only three of the most important impacts are discussed. These are: the global warming potential (GWP, figure A.6), the toxicity potential (TP, figure A.7) and the ozone layer depletion potential (ODP, figure A.8). In all this graphs, the (1) stands for the old method (ethanol made from the sugar) and the (2) stands for the new method (ethanol made from the waste of sugarcane).

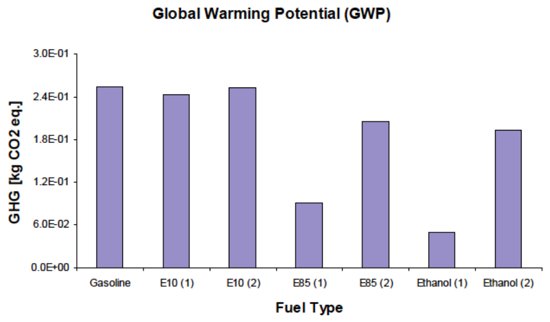

Figure A.6: Global warming potential of sugarcane made ethanol [31]

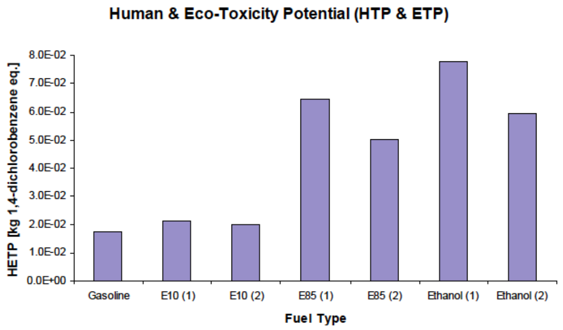

Figure A.7: Toxicity potential of sugarcane made ethanol [31]

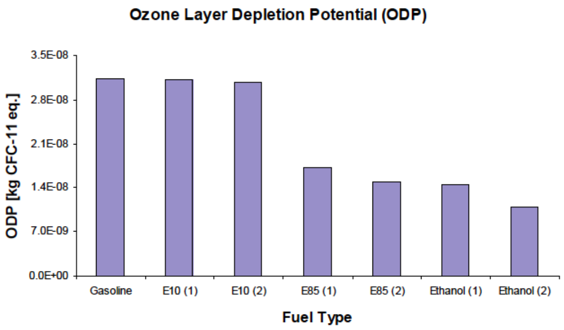

Figure A.8: Ozone layer depletion of sugarcane made ethanol [31]

Now all the figures will be discussed shortly. The GWP (figure A.6) shows that ethanol is doing better than gasoline. This is of course due to the fact that the sugarcane absorbs CO_2. Method one gives the best reduction, but this method is not the most sustainable method. Method two still has a lower GWP than gasoline but its worse than method one. But, method two is preferred because it does not influence food production.
In figure A.7 it can be seen that the TP of ethanol is worse than the one of gasoline. This is mainly because of all the toxic agrochemicals that are needed to grow the sugarcane. So in this view, gasoline is better for the environment than ethanol. In this graph can also be seen that the TP is lower for method two, so this method is preferred here.
The last factor is the ODP (which can be seen in figure A.8), which is better for ethanol. This is because crude oil or coal are worse than the agricultural emissions. Also here, method two is doing a little better.
In the end, there is no clear conclusion. Depending on what your priorities are, biofuel or gasoline will be better. At the end of this section, all the different options will be compared.

A.3 Ethanol Made from Switchgrass

The third possibility to make the ethanol from is switchgrass. Switchgrass is one of the popular lignocellulosic feedstock of the second generation ethanol production. Although it is not a residue but a crop, it can be grown on marginal lands which cannot be used for food production.

A.3.1 Life Cycle

Figure A.9 shows the life cycle of ethanol which includes all relevant processes.

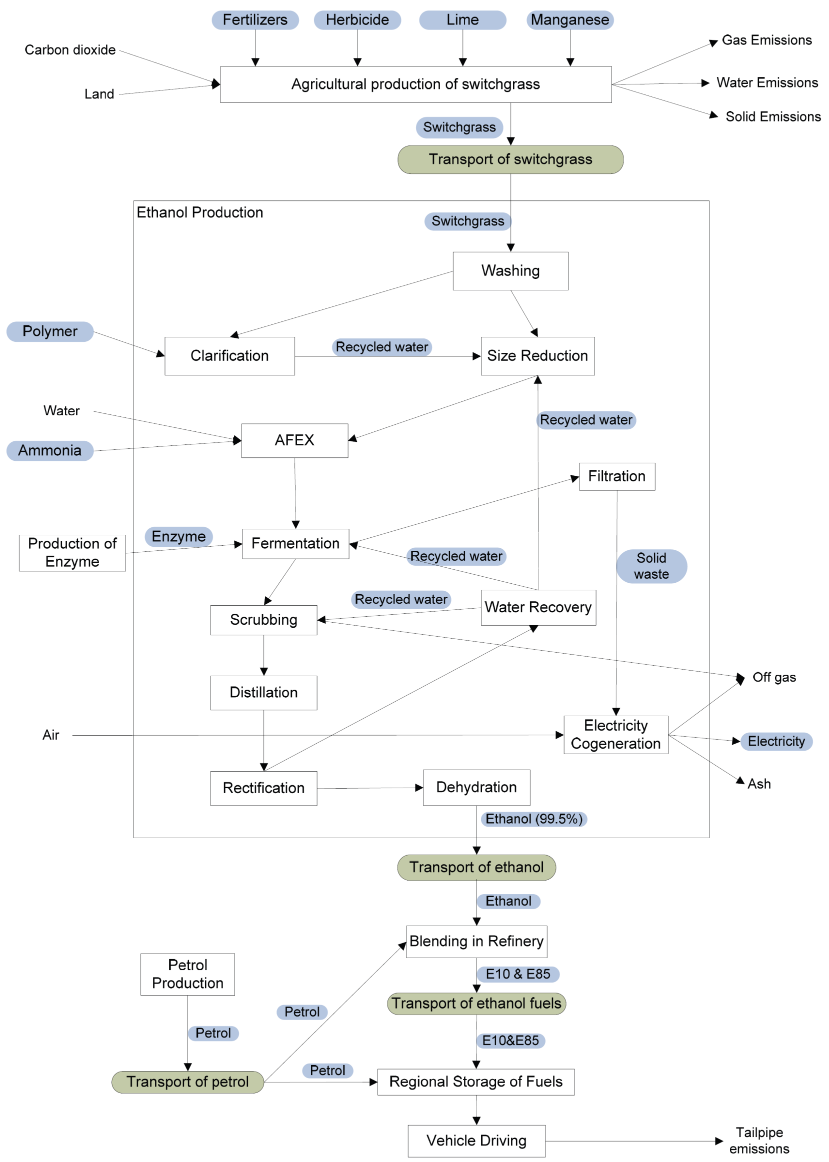

Figure A.9: Life cycle of switchgrass [31]

As visualised in figure A.9 the life cycle can be splited up in three major parts:

- Agricultural production of switchgrass
- Ethanol production
- Transportation and usage

A.3.2 Land Use

In this section it will be investigated how much land there is needed to produce the ethanol as of today. From the report written by T. Patzek [132] there is know that for each kg of switchgrass 0.38 liter of ethanol can be produced. It is also know that on one acre of land (4 047 m^2) approximately 7200 kg of switchgrass can be grown on a yearly basis. So using basic calculus there is calculated that for one litre of ethanol, approximately 1.48 m^2 is needed.
Based on section A.1.2, this means one airplane will need 26 403 m^2 per year (if one harvest a year is assumed). As a comparison, this is equal to 5.28 soccer fields.

A.3.3 Environmental Impact

As stated in the introduction of this chapter, section 14.1, only the three main environmental impact categories will be assessed. But in order to analyse the environment impact of ethanol made form switchgrass the toxicity potential (TP) will be divided into two subcategories: human toxicity potential (HTP) and eco-toxicity potential (ETP).

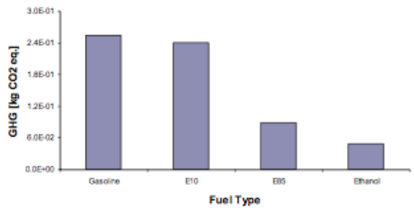

Figure A.10: Global warming potential (GWP) of switchgrass made ethanol [31]

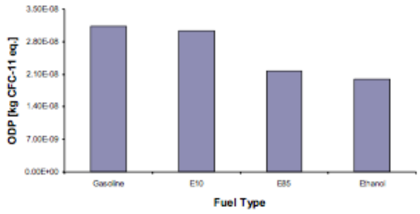

Figure A.11: Ozone layer depletion potentail (ODP) of switchgrass made ethanol [31]

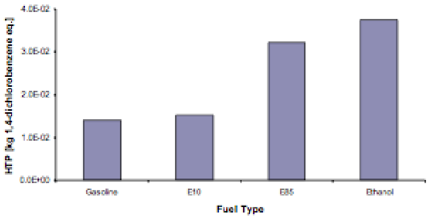

Figure A.12: Human toxicity potential (HTP) of switchgrass made ethanol [31]

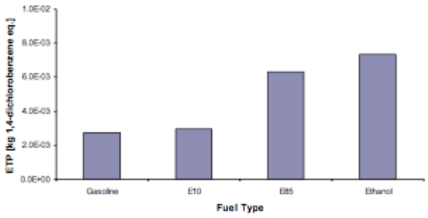

Figure A.13: Eco-toxicity potential (ETP) of switchgrass made ethanol [31]

Studying the environment impact of ethanol based on switchgrass starts with analysing the global warming potential (GWP). GWP is one of the most important issues globally. As visualised in figure A.10 ethanol made from switchgrass produces less green house gases (GHG). As can be derived from figure A.10 there can be concluded that 78 % less green house gases will be emitted when flying on ethanol compared to gasoline.
The second main category is the ozone layer depletion potential (ODP), figure A.11. There can be concluded that the ODP will also decrease when flying on ethanol in stead of gasoline. There must be noticed that the reduction in ODP when flying on ethanol compared to gasoline is about 33 %, this reduction is not as significant as the reduction in green house gases (GHG).
The third and last main category is the toxicity potential (TP), as stated before when analysing the environmental impact of switchgrass based ethanol the toxicity potential will be divided into two subcategories. In figure A.12 and figure A.13 the human toxicity potential (HTP) and the eco-toxicity potential (ETP) are visualised accordingly. There can be concluded that both the ETP and HTP will increase when flying on ethanol. Agriculture is the main contributor to the ETP and HTP, due to the use of agro-chemicals.

A.4 Ethanol Made from Waste

A.4.1 Life Cycle

This subsection of the report is generally based on a powerpoint presentation made by the chemistry department at the Texas A & M University [32].
Before the life cycle of ethanol from waste can be explained and visualised there must be started with defining the word "waste" since it is word which might contain a lot. The following "waste" is used to make ethanol:

- municipal solid waste (MSW)
- sewage sludge
- forest product residues such as wood chips, wood molasses and other wood waste

In general there are three different platforms to convert waste into ethanol. The first platform is the thermochemical platform where biomass is gasified and are then passed over a rhodium catalyst which yields ethanol. The second platform used to convert waste to ethanol is the sugar platform. The sugar platform has four main steps:

- Carbohydrates are hydrolyzed to sugars
- The sugars are fermented to ethanol and CO_2 with pure cultures
- The remaining Lignin is gasified and shifted to hydrogen
- The hydrogen reduces CO_2 to form more ethanol

The third and final platform is the carboxylate platform. The life cycle of the third platform is visualised in figure A.14.

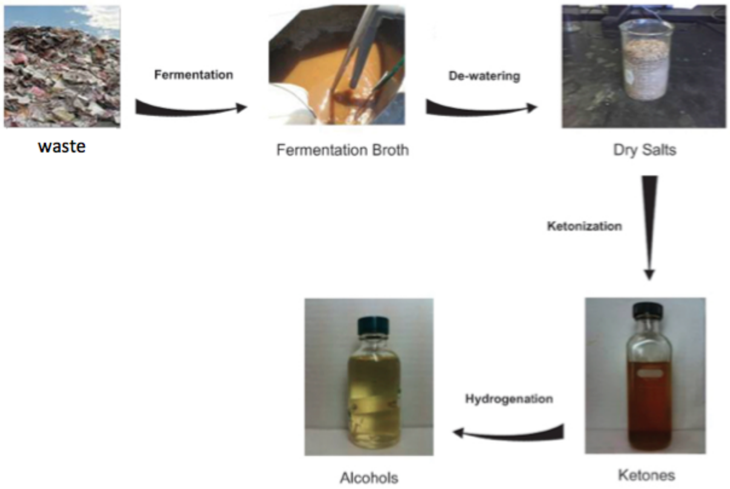

Figure A.14: Life cycle analysis of waste [32]

This platform has multiple advantages over the two other platforms to convert waste in ethanol and therefore if waste is used to propel the Cradle to Cradle® aircraft the third platform will be used. The carboxylate platform has the following advantages over the two other platforms:

- It has demonstrated higher yields than both of the other processes as visualised in figure A.15
- No enzyme addition required to produce ethanol
- Mixed cultures used are much cheaper than pure cultures

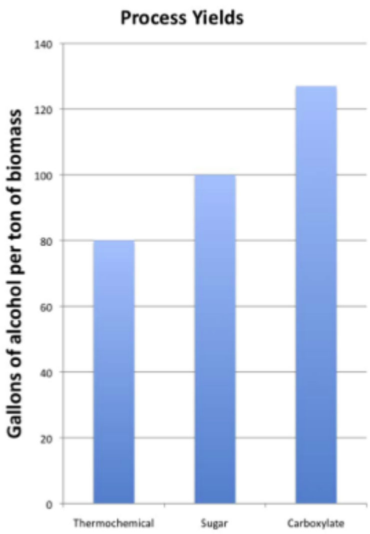

Figure A.15: Comparison between the three platforms to make waste derived ethanol [32]

A.4.2 Land Use

When using ethanol from waste no direct land will be used as which is the case for the other three sources of ethanol. In this case a certain amount of waste, in kg, will be needed.
As can be concluded from figure A.15 125 gallons of ethanol is produced per 1 000 kg of waste. When converting this to SI unit yields that for each liter of ethanol produced 2.11 kg of waste is needed.
Based on section A.1.2, this means one airplane will need 37 663.5 kg of waste on a yearly basis.
Based on source [133] there is known that on average each inhabitant of the Netherlands makes 500 kg of waste on a yearly basis. This means that the waste of 68.5 people is needed to propel one Cradle to Cradle® aircraft.

A.4.3 Environmental Impact

Compared to Gasoline

When using waste to propel the Cradle to Cradle® aircraft there can be said that based on the report written by Allen Zihao Shi [134] the green house gas (GHG) emissions will be reduced by 29.2 % to 86.1 % when flying on waste derived ethanol compared to conventional gasoline. The reduction range is very wide en this is mainly due to the unknown composition of waste.

Compared to landfill

When the waste is not used as a source to make the ethanol for the Cradle to Cradle® aicraft it will end up on landfill sites. A landfill site is a site for the disposal of waste materials by burial and is the oldest form of waste treatment a conventional landfill site is visualised in figure A.16. [135]

Figure A.16: Landfill site in Poland [135]

When the waste ends up at the landfill gases (LFG) are produced when organic material decomposes anaerobically, consisting of 45 % to 60 % methane gas, 40 % to 60 % carbon dioxide, and 2 % to 9 % other gases which are mostly emitted to the atmosphere. LFG is becoming a significant contributor to atmospheric methane, unless recovery control systems are implemented. Based on the article written by the Climate Change Connection [33] there is know that methane is 25 times as bad as carbon dioxide. This essentially means that flying with the Cradle to Cradle® aircraft, with ethanol made from waste, will reduce the amount of carbon dioxide in the air.

Appendix B | Aluminium Trade-Off

In section 18.1, automotive aluminium alloys have been identified to contribute beneficially towards the Cradle to Cradle® aircraft design. A lower material price, larger market resulting in an increased scrap value and better machinability are just a couple of them. However, several alloys exist within the automotive industry. In order to optimize the design, a total of four different automotive alloys have been analysed:

- **Aluminium 6022 (Al-6022) [94] :** The 6022 alloy uses silicon and magnesium as primary alloying elements. The alloy was specifically designed for better corrosion resistance, formability and greater strength for dent resistance after thermal exposure. Those properties make Al-6022 to be widely used within the automotive sector. Within the concept of using less high-grade and cheaper aluminium, Al-6022 could perfectly match required material properties when the aircraft life cycle is reduced.
- **Aluminium 6016 (Al-6016) [136] :** Another aluminium widely used in the automotive sector is the 6016 alloy. It has a very good formability with low spring back, good weldability and high corrosion resistance.
- **Aluminium 6061 (Al-6061) [137] :** Al-6061 is a precipitation hardening aluminium alloy with magnesium and silicon as primary alloying elements. Al-6061 provides good design opportunities because of its good mechanical properties. However, the 6061 alloy has been developed in 1935, which makes it an old-fashioned alloy today, with a reduced market share for aluminium applications today. As a large market for the aircraft's material is one of the focus points of the Cradle to Cradle® aircraft design, Al-6061 does not fit within the current aircraft design.
- **Aluminium 5086 (Al-5086) [138]:** The 5086 alloy is also a largely used material for high performance structures. Its excellent corrosion resistance makes it a suitable material for the naval industry. Because of its good welding possibilities, Al-5086 could also be an interesting alloy for aerospace structures. However, stress corrosion cracking is still a major issue of this alloy and therefore it is not suitable yet for aerospace applications.

Now that only two possible alloys are remaining, their mechanical properties can be compared in order to select a final aluminium alloy for the aircraft design. The mechanical properties can be found in table B.1.

Table B.1: Al-6016/Al-6022 properties comparison

	Al-6016 T4	**Al-6022 T4**
Tensile Yield Strength [Mpa]	143	160
Ultimate Tensile Strength [Mpa]	219	271
Elongation at failure [%]	24	28
Density [kg/m^3]	2 700	2 700

Looking at table B.1 it can be seen that both materials have approximately the same density. However, the Al-6022 alloy performs much better on both its yield and ultimate tensile strength. For that reason, Al-6022 has been selected to be the material used for the aircraft's structure. Even though material stiffness would have been another important mechanical property for the comparison, due to lack of information on the Al-6016 alloy, this property has not been included in the table.

Appendix C | Joining Methods

C.1 Joining Methods

In this section, a description is given of all the relevant joining methods that can be applied to the aircraft design. The relevant joining methods can be divided into three groups: welding, mechanical joints and adhesive bonding.

C.1.1 Welding

Resistance Spot Welding (RSW)

RSW is a commonly used welding method in the automotive industry. The method is very suitable for sheet metal and can be applied at high speeds in an automated process. Due to the extensive use of this technique, RSW is very reliable. The downside of this method is that a very high current is required, thus large batteries. By using RSW warping of the material occurs, which reduces the fatigue strength. Internal cracking occurs and the corrosive properties of the material are affected [139].

Laser Beam Welding (LBW)

LBW is a relatively new welding technique based on a high focus energy density beam capable of producing narrow welds. LBW is applied on one side of the material and there is no contact between the welding device and the material. The advantage of LBW is that the technique can be used at atmospheric pressure. The energy input of this method is relatively low compared to arc welding processes (creating an electric arc between an electrode and the base material to melt), however this technique requires inert gas shielding. LBW can be applied in an automated, reliable and repeatable working environment [140].

Friction Stir Welding (FSW)

Friction Stir Welding is a relatively new technique in the aircraft industry. Being used for the first time in the late 1990's, it showed improvements in efficiency, strength and work time. This also resulted in a decrease in weight and costs. The method is very suitable for aluminium, is environmentally benign (no gases nor fillers required) and is applicable to both butt and lap joints [141]. A drawback is that the method requires pressure on both sides of the material, yielding complexity in production. The method is illustrated in figure C.1.

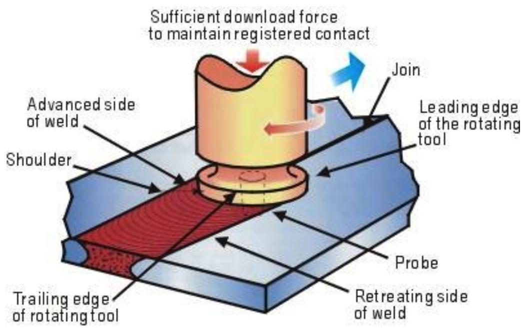

Figure C.1: Illustration of the FSW process [142]

C.1.2 Mechanical Joints

Riveting

Rivets are used in almost every aircraft design. Since rivets are plastically deformed and fill the entire pre-drilled hole, they provide excellent properties in shear. Tensile loading (parallel to the axis of symmetry of the rivet) must be avoided to ensure structural safety. Rivets can be made from different materials. On one hand, the same material as the sheet metal can be used, which simplifies the recyclability (melting) to a great extend. On the other hand,advanced aluminium-magnesium alloys can be used to provide stronger joints [143].

Bolting

Bolts are used to join critical parts that need frequent disassembly, such as locations that need regular maintenance and inspection. Bolts are excellent in tension but a disadvantage is that weight is added to the structure. When the bolt is pre-tensioned, the cyclic loads can be reduced, which enhances the fatigue life [144] [145]. At end-of-life of the aircraft the bolts can easily be removed, hence the disassembly can be performed very quickly (and cheap). Bolts need to be inspected regularly, since the aircraft cycles may cause the nuts to loosen.

C.1.3 Adhesive Bonding

Adhesive bonding is a joining method using a polymer to adhere two components. Via the polymer, the load is transferred over the interface of one part. Adhesive bonding is used mainly for attaching stringers to fuselage and wing skins to stiffen the structures against buckling. Bonding an aircraft structure together with adhesives offers long-term benefits [146] [105]:

- An adhesively bonded joint has no holes and is therefore less sensitive to fatigue compared with mechanical fasteners . Therefore, it can be assumed that no in-plane stress concentrations occur.
- By using adhesives, the structural properties do not degrade since there are no holes.
- A bonded joint has a better corrosion resistance compared with other joining methods and can be air- and liquid tight.
- Adhesive bonding enables the joining of metal with polymers. This is required for the joining of the secondary structures with the primary ones.

However, adhesive bonding also implies some crucial disadvantages

- The manufacturing processes for adhesively bonded structures are complicated. A pre-treatment has to be applied and often, high temperatures and pressures are required.
- Nowadays, a bonded joint is not suitable for disassembly.
- A bonded joint may only be loaded in shear, transversely.

C.2 Bolt Sizing

AN-bolts are frequently used, certified bolts in the aerospace industry. These typically have a hexagon shaped head and a shank that fits into the hole. The size, material, etc of a bolt is identified by the number combination after AN. An example is as follows:

AN4-8A

- AN- means the bolt is manufacturted according to Air Force-Navy specifications
- 4- identifies the diameter of the bolt shank in 1/16 inch increments.
- 8- identifies the length of the sank in 1/8 inch increments
- A-means the shank of the bolt is undrilled. No letter here means a drilled shank

An impression of such a bolt can be found in figure C.2 [147].

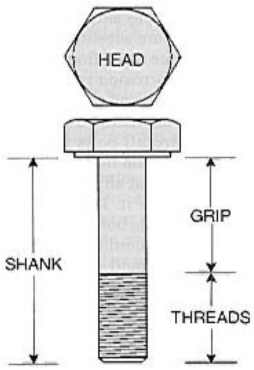

Figure C.2: Bolt layout [147]

The bolt will be selected such that the grip length equals the material thickness that is being by the bolt or slightly longer. Furhermore, the bolt length must be sufficient to ensure no more than one thread will be inside the bolt hole. In case the bolt is longer, a washer can be used [148].

One remark during the manufacturing of bolts has to be made: It is important that the bolt is not under- or overtightened. This may lead to an increase of stress on the bolt which is negatively for the structure. Therefore, the use of a torque wrench is recommended [147].

Appendix D | Datasheet Duraform Thermoplastic Composite

This datasheet is obtained from [149].

SINTERING

DuraForm® HST Composite

For use with all Sinterstation® Pro and Sinterstation® HiQ™ series SLS® Systems

Technical Data

General Properties

Measurement	Condition	Metric	U.S.
Specific Gravity	ASTM D792	1.20 g/cm^3	1.20 g/cm^3

Mechanical Properties

Measurement	Condition	Metric		U.S.	
		X-direction	Z-direction	X-direction	Z-direction
Tensile Strength, Yield	ASTM D638	N/A*		N/A*	
Tensile Strength, Ultimate	ASTM D638	48-51 MPa	31-34 MPa	7050-7350 psi	4500-4900 psi
Tensile Modulus	ASTM D638	5475-5725 MPa	2900-3000 MPa	795-831 ksi	421-434 ksi
Elongation at Yield	ASTM D638	N/A		N/A	
Elongation at Break	ASTM D638	4.5 %	2.7 %	4.5 %	2.7 %
Flexural Strength, Yield	ASTM D790	N/A		N/A	
Flexural Strength, Ultimate	ASTM D790	83-89 MPa	64-68 MPa	12000-12900 psi	9275-9850 psi
Flexural Modulus	ASTM D790	4400-4550 MPa	2625-2825 MPa	638-660 ksi	381-410 ksi
Hardness, Shore D	ASTM D2240	75		75	
Impact Strength (notched Izod, 23 °C)	ASTM D256	37.4 J/m		0.7 ft-lb/in	
Impact Strength (unnotched Izod, 23 °C)	ASTM D256	310 J/m		5.8 ft-lb/in	
Gardner Impact	ASTM D5420	5 J		3.7 ft-lb	

Thermal Properties

Measurement	Condition	Metric		U.S.	
		X-direction	Z-direction	X-direction	Z-direction
Heat Deflection Temperature (HDT)	ASTM D648 @ 0.45 MPa @ 1.82 MPa	184 °C 179 °C	178.8 °C 135 °C	363 °F 355 °F	354 °F 276 °F
Coefficient of Thermal Expansion	ASTM E831 @ 0 - 50 °C @ 85 -145 °C	138.3 µm/m-°C 267.2 µm/m-°C	102.7 µm/m-°C 184.2 µm/m-°C	76.8 µin/in-°F 148.4 µin/in-°F	57 µin/in-°F 102.3 µin/in-°F
Specific Heat Capacity	ASTM E1269	1.503 J/g-°C		0.359 BTU/lb-°F	
Flammability (3 mm)	UL 94	HB		HB	

Electrical Properties

Measurement	Condition	Metric	U.S.
Volume Resistivity	ASTM D257	6.7 x 10^{15} ohm-cm	6.7 x 10^{15} ohm-cm
Surface Resistivity	ASTM D257	5.2 x 10^{15} ohm	5.2 x 10^{15} ohm
Dissipation Factor, 1 KHz	ASTM D150	0.028	0.028
Dielectric Constant, 1 KHz	ASTM D150	3.14	3.14
Dielectric Strength	ASTM D149	18.5 kV/mm	470 kV/in

* N/A = Not Applicable

Data was generated by building parts using 100% virgin powder under typical default parameters. DuraForm® HST Composite was processed on a Sinterstation® HiQ™ + HS SLS® System at 25 watts laser power, 10 m/sec [400 inches/sec] scan speed, and a powder layer thickness of 0.1 mm [0.004 inches].

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Appendix E | Disassemble Methods

Several disassembly methods have been analysed in order to improve the end-of-life phase of the aircraft. The current analysis will only look at the disassembly of welded joints, as riveted joints do not have to be disassembled separately because of the uni-material aluminium structure.

E.1 Laser Cutting

A first possibility for the aluminium cutting is the use of the laser cutting technique. Laser cutting combines a high-power laser and an inert gas in order to burn off the material at the cutting line . Often used gases are CO_2 and neodymium.

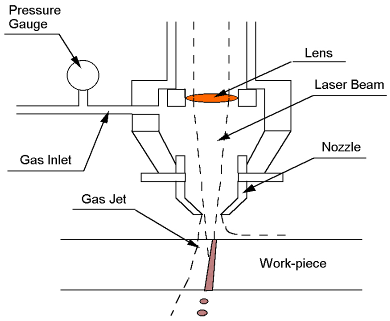

Figure E.1: The laser cutting principle [150]

The major disadvantages of laser cutting are that dust and gas emissions will be created during the cutting and that it requires a lot of energy. Both of these disadvantages make it difficult to implement laser cutting within the Cradle to Cradle® philosophy.

E.2 Abrasive Waterjet Cutting

The principle of waterjet cutting is to cut the material by using a beam of highly pressurized water. In order to allow cutting of high strength materials, abrasive waterjet cutting reinforces the beam of water with abrasive particles, which can be seen in figure E.2. By using those particles, abrasive waterjet cutting has become a widely used cutting tool in the aerospace industry. Some of the reasons for its success are listed below: [151].

- No heat affected zone
- Good accuracy
- Little material loss

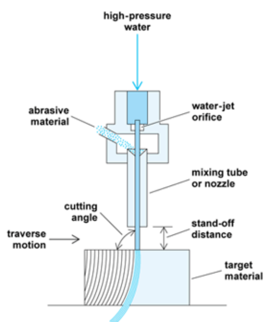

Figure E.2: The abrasive waterjet cutting principle [152]

Within the Cradle to Cradle® philosophy, abrasive waterjet cutting has the following additional advantages:

- Both the water and abrasive particles used for the cutting process can be fully recycled, allowing a perfect integration within the Cradle to Cradle® philosophy [153].
- Approximately 10 % less energy required compared to laser cutting [154].

All of the advantages above make abrasive waterjet cutting extremely suitable to be used for the disassembly of the Cradle to Cradle® aircraft.

E.3 Saw Cutting

A final possibility for the cutting of the aircraft's structure is the very basic method of saw cutting (figure E.3).
The main disadvantages of saw cutting are:

- Rough edges: Saw cutting results in rougher edges compared to the other cutting methods. This is however not implying any issues for its current application as the structure is only cut in order to remelt the aluminium.
- Limited large-scale possibilities: Saw cutting can only be used on rather small structures. Within the context of the InfiniCraft saw cutting should not provide any problems.

Saw cutting also provides some advantages within the context of the Cradle to Cradle® aircraft design:

- Low energy is required for the sawing process, compared to the other cutting processes
- The fact that no expensive equipment is required for the process implies a reduction in the total cost of the end-of-life phase of the aircraft.

Figure E.3: The saw cutting principle

Appendix F | Weight Estimation Update

In this appendix, the final class II weight estimation is described. This appendix is the follow-up of chapter 9. In chapter 9 the baseline weight estimation is discussed that was used for the structural sizing and fuel tank sizing. Now that all analyses have been performed, the weight estimation can be updated and finalized. The method that is used is described in the books of Roskam [21].

Together with updating the weight estimation, some changes are made to the components in the estimation. From Roskam [21] a list with standard components for single propeller, general aviation aircraft has been used to decide which components should be estimated. During the design it became clear that the auxiliary power, auxiliary gear, paint and API (air-conditioning, pressurisation and anti- and de-icing systems) are not present on the aircraft, or do not take up a significant portion of the weight. These have as such not been included in the weight estimation. Finally, also the interior has been included. The results are shown in figure F.1.

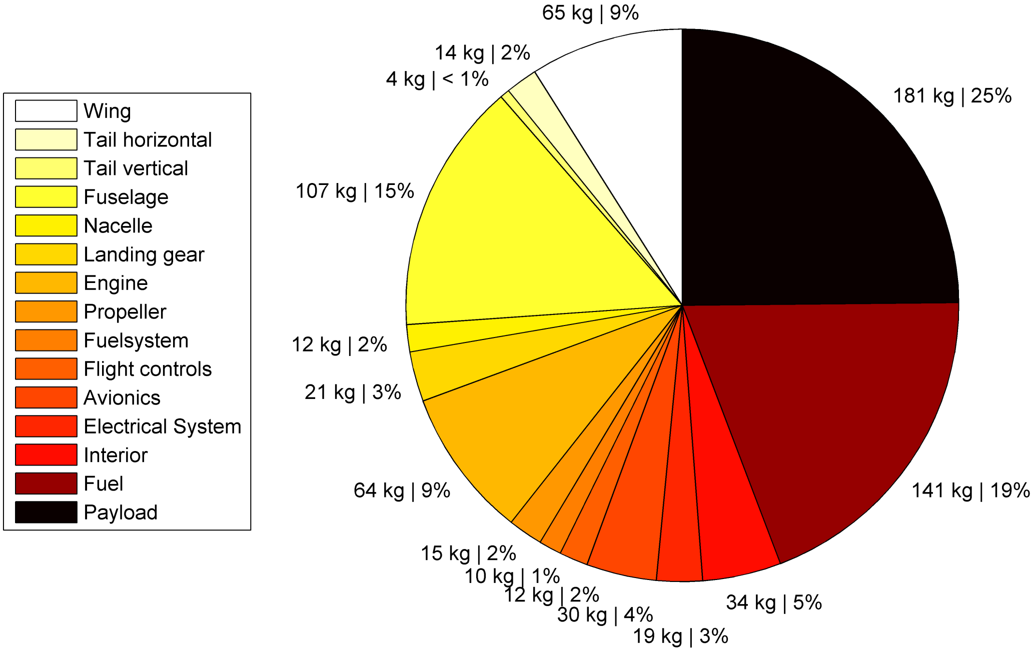

Figure F.1: Updated and final class II weight estimation of the InfiniCraft

The components can be added up to yield an OEW of 407 kg and a MTOW of 730 kg. The weight has slightly increased since the baseline weight estimation (with about 30 kg). This can be explained by the inclusion of the interior weight and the fact that the flight control weight was not estimated correctly in the previous version. Furthermore, more loops were made between the wing and power loading of 664 N/m^2 and 0.09 N/W, to get the most accurate weight estimation. This does however increase the weight as well, as the wing size is slightly increased every time the weight increases, which yields again a higher weight.

In further design stages, it is very important to make more design iterations. When this is done, the weight development should be monitored very closely. A weight overshoot is a significant threat to the InfiniCraft, because of the use of ethanol (which has a lower energy density) and the Al-6022 alloy. The design of different components should as such be done with the weight as an important criterion.

For now there is however no reason to worry, since the weight is currently very comparable to reference aircraft. For example, the Cessna Skycatcher [155] has an OEW of 377 kg, which is only 7 % lower and a MTOW of 599 kg, which is 18 % lower. This can be explained by the lower energy density of the ethanol, the larger range of the InfiniCraft (1 000 km against 815 km, as discussed in chapter 29) and the larger effective payload capacity of the InfiniCraft (181 kg against 141 kg [16]).

Appendix G | Processing materials

In this chapter the detailed processing of the various materials from the InfiniCraft is discussed. First the aluminium and steel recycling will be discussed. After this, the TPC and polycarbonate material recycling will be looked upon. Next, rubber and wood will be handled. Thereafter, the various fluids and the engine block will be explained. In the next sections, the instruments & avionics, lights and electric wire recycling will be discussed and finally the interior will be treated.

G.1 Aluminium Recycling

One of the main reasons why the team has chosen to use aluminium for the primary structure are its good recycling possibilities. According to the class II weight estimation, the aluminium structure is going to account for 46 percent of the total aircraft OEW. Therefore a detailed recycling analysis of Al-6022 has to be performed. All of the aluminium recycling explanation below is based on [156].

The Aluminium Recycling Process

Since 1980, the aluminium recycling industry has quadrupled its annual output [157]. In order to achieve maximal efficiency from the recycling process, recycling methods and techniques have been updated and invented on a continuous base. The total process can be divided into four major sub phases.

De-Coating: In order to improve the end-of-life performance of the aircraft, an easy paint removal technique should be used. A previously widely used painting remover was methylene chloride. It is very effective and results in an easy and quick paint removal process. However, its carcinogenic behaviour makes methylene chloride undesirable in any paint removing process. Alternative stripping possibilities are treated below [158]:

- **Benzyl alcohol:** One possible replacement of methylene chloride is benzyl alcohol. This paint remover does not contain any harmful air pollutants (HAM's) which make it Cradle to Cradle® proof. Special care has to be taken into account for the use of benzyl alcohol on high strength steel and magnesium as it tends to embrittle them. This problem however does not occur on aluminium applications. The only drawback of benzyl alcohol is the time consuming process to fully remove the paint, as it takes up to 25% more time compared to methylene chloride.
- **Hydrogen peroxide:** Hydrogen peroxide (H_2O_2) used for aircraft painting removal breaks down in oxygen and water and does not contain any harmful air pollutants which makes hydrogen peroxide an environmental friendly painting stripper. The effectiveness of hydrogen peroxide is also high compared to benzyl alcohol, which makes the time required for the removal process shorter. It's waste management only consists of a water refinement process from the hydrogen peroxide.

According to the above explanation, the conclusion is made that paint removal can be done in an environmental friendly way. H_2O_2 seems to be the most interesting paint stripper as it implies a less time-consuming process.

Shredder: In order to melt the aluminium, it first has to be cut in small pieces. This shredding process will be a simple shreddering since no sorting of different materials is required.

Melting: As the complete aircraft structure will be uni-material, there is no need to perform further material separation. The scrap aluminium from the shredder can progress immediately into the melting phase.
The melting of the recycled aluminium is the main energy consumer within the end-of-life phase of the aircraft. Still, the recycled aluminium will only require 5 % of the energy required for initial generation of aluminium [159]. Salt is added to the meting process in order to reduce the creation of an oxide layer.

Refinement and reintegration: During the refinement of the aluminium, it is transferred to a holding furnace and alloying particles can be added again in case the aluminium is exceeding the allowable tolerances in the material's composition. Grain refiners are used in order to achieve the required metallurgical structure of the aluminium.

Once the Al-6022 alloy is refined, it can be prepared for a reintegration into the technical cycle of either the aerospace or automotive sector. Depending on its application, the molten aluminium can be delivered in the following forms:

- **Molten:** The aluminium leaves the process in molten state in order to cast it immediately into new parts.
- **Ingot:** Rolling of the ingot can result in sheet, foil, plate, wire, rod, and bar products.

The aluminium is now called secondary aluminium, but still maintains the same properties as before as it is still exactly the same Al-6022 alloy [160].

Advantages of the current design

The above topic described the recycling process for the aluminium structure of the Cradle to Cradle® aircraft, using the automotive Al-6022 alloy. However, as today's structures are more complex and constructed out of multiple materials, the actual recycling process of today's aluminium structures is much more advanced, time-consuming and expensive. The total aluminium recycling process of modern cars can be seen in figure G.1.

When the structure has been disassembled and shreddered, four different processes are used to filter the aluminium alloy from impurities. In a final stage, different alloys are separated as those have to be melted separately in order to obtain exactly the same alloys again after the melting. Non of those processes has to be implemented in the recycling process of the Cradle to Cradle® aircraft and are therefore shown in dark in figure G.1. For this reason, the recycling of the primary structure of the aircraft can be done at lower cost compared to modern cars and aircraft.

Another advantage of the current design is the use of typical automotive alloys. Therefore the market for the recycled aluminium is much bigger compared to the relatively small aerospace market. This means that more value can be earned from the scrap and better selling points for the aluminium can be found. The aluminium can both be recycled and sold locally, reducing the transportation costs & impact of the end-of-life phase of the aircraft. This will be treated in much more detail in part V.

All of these advantages should work both as a proof of the economical benefits of aircraft end-of-life management and as incentive to stimulate current aircraft manufacturers in designing their aircraft with a specific focus on the end-of-life possibilities for the general aviation market.

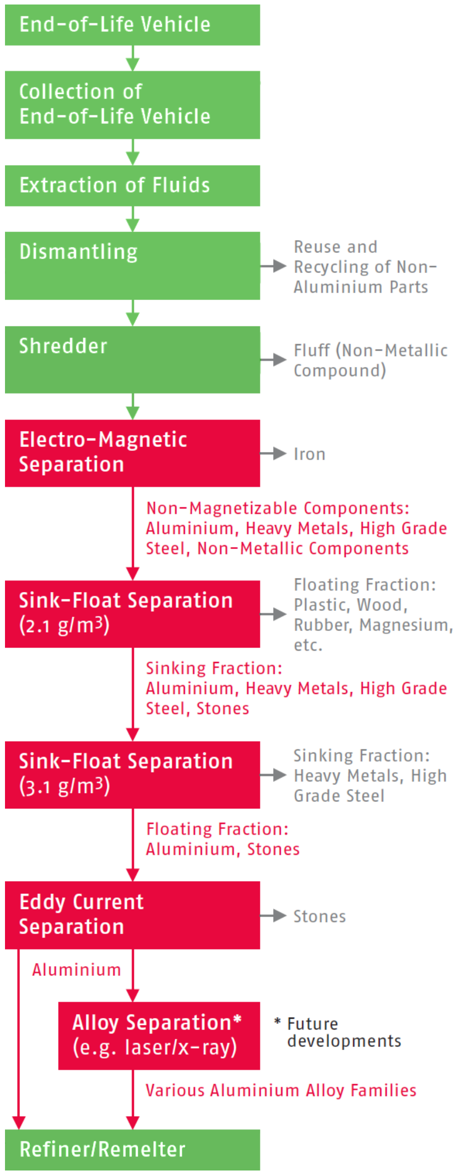

Figure G.1: The aluminium recycling process for a modern passenger car [156]

G.2 Steel Recycling

Steel has been used in the aircraft's design for the bolts, control cables and antenna. Steel is one of the most recycled materials in the world, which makes it a good material within the Cradle to Cradle® principle. The recycling process for steel follows the same principle steps as aluminium recycling, which has been treated before. The use of recycled steel results in 75 % energy savings and a CO_2 reduction of 80 % [161]. All of the benefits of the current Cradle to Cradle® aircraft design mentioned for the aluminium recycling are also present for the steel recycling, as none of the filtering and alloy separation methods are required for the uni-steel constructed bolts, control cables and antenna.

Differences with the Aluminium Recycling process

The only major difference between steel and aluminium recycling is the melting method. While aluminium melting doesn't require special furnace specifications, the melting of scrap steel specifically requires an electric arc furnace (EAF). Other steel recycling methods such as basic oxygen steelmaking (BOS) can only use 35 % of scrap steel together with 65 % of primary steel.

EAF heats the charged steel by use of an electric arc. Even though this process allows the production of secondary steel out of 100 % scrap material, EAF still induces some environmental issues [162] :

- Dust collection from process gasses
- Cooling water demand
- Slag production

G.3 Thermoplastic Composites Recycling

As described in section 21.4, the secondary thermoplastic composites will be 3D- printed. The benefit of this is that a part can be locally printed if it has to be replaced. Since 3D-printing is a novel technique, assumptions have to be made concerning the printing of thermoplastic composites in 2025. Therefore also assumptions concerning the recyclability of printed thermoplastic composites will be made. In order to do so, the recyclability of thermoplastic composites and 3D printed materials will be described separately. Afterwards, those two processes will be combined to come up with a solution for the processing of 3D-printed thermoplastic composite secondary structures.

Thermoplastic Composites

Advanced composite materials are being used more and more in structural applications and therefore the recycling of these materials is an upcoming challenge. G. Shinner, J. Brandt and H. Richter discussed two approaches for the recycling of carbon-fiber reinforced thermoplastic composites. The first one focuses on the grinding of TPCs in order to use the various grinding fractions as a high-quality reinforcing material in injection molds or as press molding compounds. The properties evaluated are on the same level as comparable injection molding materials. Another approach investigated for reusing thermoplastic carbon-fiber-reinforced composite parts is a reforming process. The performed reforming experiments did not change the evaluated material properties. [163]
Furthermore, laboratory tests demonstrated that it is possible to grind and remelt short-fibre reinforced thermoplastics many times with little loss of structural performance [164].
It can be concluded that the recycling of composite materials is an upcoming challenge in which already a lot of research is going on. Because the handling of composites in the EOL phase is nowadays still rare and processes are not yet optimised, there is still a little loss of structural performance after recycling. The assumption can be made that by 2025, the recycling process will be optimised and that it will fit completely within the Cradle to Cradle® philosophy.

3D-printing

Researchers at Michigan Technological University have created a plastic extruder that turns home recyclables into usable filament for 3D printing. The machine takes 10 cm pieces of plastic and shreds them, before melting the plastic and extruding it through changeable nozzles, and shaping it for use in printers. An impression of this extruder is shown in figure G.2. Although this extruder is used for home made materials, the feasibility of extruding plastics as resin for 3D printers has been proven. Therefore, it can be assumed that in 2025, tools are developed which can recycle thermoplastics into a resin for 3D-printing. For compression moulding, only the recyclability of thermoplastic composites has to be taken into account. Therefore, this is a good alternative if 3D-printing is not feasible [165].

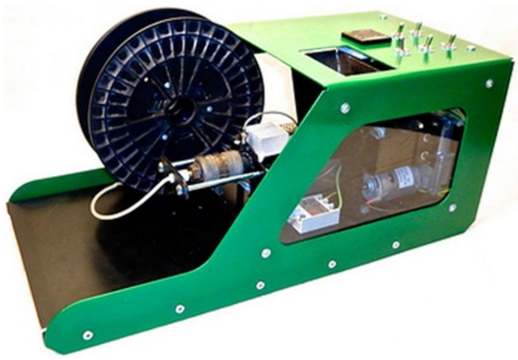

Figure G.2: Extruder for 3D printer resin [165]

From these analyses, it can be assumed that in 2025, it should be feasible to recycle the thermoplastic secondary structures of the InfiniCraft. Thanks to an increase in research on the recycling of composites, the losses in structural performance will be minimised in 2025. In section 21.4, compression moulding is suggested as alternative if 3D-printing and its recycling process is not feasible in 2025.

G.4 Polycarbonate Recycling

Polycarbonates are a particular group of thermoplastic polymers, which can easily be worked, molded, and thermoformed. Thanks to these properties, polycarbonates have many applications, also in the aerospace industry, as described in section 21.3. Polycarbonates exhibit favorable behaviour in both mechanical and chemical recycling [166].

- **Mechanical recycling by melting and regranulation of the used polycarbonate**
  As shown in figure G.3, mechanical recycling involves a number of treatments which include the shreddering of the material, removal of dirt and extrusion in order to create the recycled resin. Extrusion is the step which requires most energy in the process. In order to reduce energy, optimised equipment is required. Another low-cost method for saving energy is minimising the use of compressed air. Furthermore, insulation of the equipment is important to reduce the heat for the system. For example, well isolated equipment can reduce the energy cost with 35%-60% [167].
- **Chemical recycling**
  An efficient process for the chemical recycling of polycarbonate (PC) waste into diols of bisphenol A (BPA) for use as raw materials in PU production has been developed. With these raw materials, polycarbonate can be created again which makes this process fit in the Cradle to Cradle®-philosophy. However, in order to reach that, the chemicals used for this have to be "green" as well. Research has already been done to approach the chemical recycling in an ecological way of which the conclusion was that it is possible and with the suggestion to use methanol and methanol-water mixture to recycle polycarbonate [168] [169].

From these two methods, mechanical recycling will be used to process polycarbonates from the InfiniCraft. When using the chemical method, the basic molecules are obtained. This means that chemical reactions are required to remake polycarbonate, which will lead to extra production processes and hence an increase in cost. Although the chemical process can happen in an ecological way, the regranulation of polycarbonate fits better in the Cradle to Cradle® concept. Research is going on to reduce the costs & energy use for this process [167].

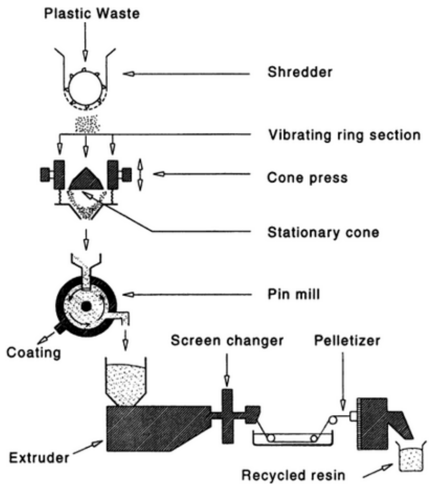

Figure G.3: Process for the mechanical recycling of plastics

The influence of reprocessing on the properties of polycarbonate has been investigated by A. Chrysostomou and S. Hashemi [170]: "It was found that reprocessing does not affect the tensile strength, flexural strength and flexural modulus of the polycarbonate material. Fracture parameters such as fracture toughness and the material resistance to crack propagation also showed no variation with the number of reprocessing cycles, although both were strongly dependent on the sample width. Dynamic mechanical analysis (DMA) also indicated that reprocessing has no significant effect upon dynamic mechanical properties of polycarbonate. Results further indicated that the glass transition temperature of polycarbonate is not affected by reprocessing, only the range over which it occurs seems to be broadened by reprocessing due to increase in molecular weight with the number of reprocessing cycles."

G.5 Rubber Recycling

The rubber coming from the tires applied to the landing gear deals with large forces in landing conditions. These tires therefore wear at a fast rate. As rubber is not biodegradable, a solution has to be sought in order to recycle it. It is estimated that in the US alone, a total of 111.5 million scrap tires are stockpiled [171]. In order to create a fully Cradle to Cradle® aircraft, a proper solution needs to be implemented in order to prevent more tires to be stockpiled.

Lehigh Technologies, a company specialised in tire retrieval and processing, provides a solution to scrap tire disposal [172]. After retrieving metal particles with magnets from scrap rubber, they cool the rubber which can be shredded to fine rubber particles. After several complementary processes, they create high quality rubber particles which can serve as additives to a number of application. A few examples are listed below.

- Additive to glue tiles
- Additive to paints

- Improve moisture resistance
- Additive to rethreading materials of tires
- Additive to asphalt rubber

It should be noted however that the processing of these applications should allow for rubber retrieval at the end of life of the application. To conclude, when carefully choosing processors of the rubber tires and applications, the loop of rubber material can be closed, with the sidenote that this process is downcycling the rubber.

G.6 Wood Recycling

The InfiniCraft's propeller will be manufactured from wood. This material provides good recycling possibilities and reduced energy supply for the regeneration of new wood. The recycling process of wood consists of reducing, cleaning and sieving the wood waste. Any impurities, which are still left after those steps, are removed manually at the conveyor belt [173].

G.7 Fluid Recycling

In total three different fluids were identified to be used within the aircraft: Engine coolant, motor oil and hydraulic brake fluid. The recycling of each of those fluids will be treated separately.

Engine Coolant Recycling: Before the engine itself can be recycled, all of the engine liquids have to be removed and recycled separately. From chapter 15, NPG+ has been selected to be used as engine coolant. In order to develop a recycling process for this coolant, its main components are identified to be ethylene glycol and propylene glycol. The recycling process of glycols is based on the vacuum destillation process [174]. This process separates both glycols, after which they are purified, treated with proprietary additives and reused for new engine coolants. The recycled coolant has the advantages of being produced environmental friendly and at the same time at lower production cost. This avoids downcycling of the fluid and makes it to fit perfectly within the Cradle to Cradle® principle.

Motor Oil Recycling: Engine lubrication is required for a smooth engine operation. The recycling of this motor oil is based on conventional refinery technologies [175]. First, vacuum distillation is used to remove the 5 to 7 % of water, which has entered the oil throughout its operational use. Thereafter wiped-film evaporation removes contaminants and additives. As a final phase of the recycling process, hydrotreating is used to infuse the hydrogen into hydrocarbon molecules. At the end of the oil recycling process, new high-quality oil is generated.

Hydraulic Brake Fluid Recycling: Brake fluids are not hazardous unless they contain certain additives or they become contaminated with brake cleaner or other solvents [176]. As brake oil is not part of the mineral oil family, mixing waste brake fluid with waste motor oil absolutely has to be avoided. The total brake fluid recycling process consists of three different stages [177]:

1. Pre-filtering
2. Pre-heater
3. Oil purification and separator

The overall efficiency of the fluid recycling equals around 95% [177].

G.8 Engine Recycling

As discussed in chapter 15, the engine will be resold to other parties or the original manufacturer after 2 000 hours of operation. It can then be used in lower demanding applications. When the engine breaks down or when it is no longer needed, up to 96.4 % of the materials can be recycled. This number is multiplied with a factor of 0.9 to account for losses during the engine dismantling. A detailed analysis of the various components is also given in chapter 15.

G.9 Instruments and Avionics Recycling

The avionics consist of some basic instruments, an electronic box to gather all the aircraft information and a radio for communication as explained in section 23.2.
The basic instruments consist of many different elements. Some are fairly simple and consist only of a gyroscope, but others have pressure devices, gear boxes etc [178]. It is assumed that special techniques of instrument recycling will exist when the first instruments of the InfiniCraft need to be recycled. As these parts can be used in multiple

life cycles as discussed in section 24.4, the first recycling process of the instruments will probably only have to start after 2040. The electronic box and radio & navigation/landing equipment can be recycled in various ways [179]. A lot of manufactures provide a recycling service in which they take back their own products [180]. The disassembly process contains three phases [181]:

1. The reuse of components has first priority (resistors, capacitors, etc.).
2. Dismantling the hazardous components is essential.
3. It is common to dismantle highly valuable components and hight grade materials such as printed circuit boards, cables and engineering plastics in order to simplify the subsequent recovery of materials.

When recycling consumer electronics, the main materials are aluminium, glass, iron, copper and plastics among others in much lower concentrations [182] The recycling rate of each electronic product is different, but in general it can be said that most of the electronics can be fully recycled. Due to the difficulties in the disassembly of the circuit boards, also in this case a factor of 0.9 is applied.

G.10 Lights Recycling

The lights of the aircraft will be made out of LED lights. These have a high efficiency, do not weight as much as conventional lights and can easily be recycled. LED lights can last up to 25 years and are up to 80 percent more efficient than current incandescent lights [183].
LED lights are up to 95 % recyclable since they do not contain harmful metals or chemicals. [184]. LED bulbs are crushed and the materials are separated into glass, aluminium, electrical circuits and a small fraction of other components. The crushed glass is recovered and recycled to make new glass products [185]. The aluminium is collected for processing with the primary structure. The electrical circuits are processed together with the avionics.

G.11 Electric Wiring Recycling

The electric wires in the InfiniCraft are insulated so that no short circuits or faults can be introduced in the electrical system of the aircraft. This insulation can however be difficult to detach from the cable during the end-of-life phase. Two types of mechanical separation are available: choppers and strippers [186].
Cable choppers just cut the wire and the insulation together and use a physical process to separate the insulation and the aluminium wire. The process is very fast, but requires several steps in order to have an effective separation. Cable strippers separate the wire and the insulation using a knife. The throughput of the process is slower, but has as advantage that only one step needs to be done to have the wires and insulation separated. Another advantage is that the materials are separated without any contamination or mixing [187].
Since the InfiniCraft is a small general aviation aircraft and no fly-by-wire is used, the amount of cables in the fuselage is small. It can be concluded that the cable stripping process is more suitable for the cable recycling of this design.

The obtained aluminium can be recycled in the same way as the aluminium from the primary structure. The insulation will be made from an ecological material called EcoWire™. It not only provides lower weight for the same insulation capacity as PVC [188], it also has a much lower ecological impact and does not contain any halogenic substances which are banned from aviation [189]. The thermoplastic material can easily be melted and be reused as insulation for other wires.

G.12 Interior Recycling

The load supporting cockpit structure will be made from Al-6022. The covering will be made out a Cradle to Cradle®-certified material, selected by the customer.
The seats are composed out of an aluminium 6022 construction, which is bolted to the fuselage. The recycling of the aluminium construction is described in section G.1. The cover of the seats can be chosen by the customer from a list with Cradle to Cradle®-certified products. Therefore, it is already guaranteed that this material will be processed in an ecological way. An example of materials which can be used are described in section 21.2. It can be concluded the interior will be fully recyclable if the Al-6022 and Cradle to Cradle® materials can easily be separated.

Appendix H | Recycle Rate Calculation

In the following table, a detailed recyclability analysis of the aircraft can be found. For every component, the most important materials are listed. The mass fractions in the second column are estimated based on the experience gained from the previous ten weeks. The mass for each component is obtained from the class II weight estimation in appendix F. The masses for the materials are based on the mass fractions from column two. In the next column, the recylability rate (RR) as defined in section 24.6 is stated. For each component the recycled and waste material is computed. Finally, all masses are summed and a global recycling rate of 93.4 % is obtained.

Component	Mass fraction	Mass [kg]	RR [%]	Recycled [kg]	Waste [kg]
Wing		65,0	94,9	61,7	3,3
Aluminium	72,8	47,3	98,0	46,4	0,9
TPC	20,0	13,0	98,0	12,7	0,3
Steel	4,0	2,6	98,0	2,5	0,1
Paint	3,2	2,1	0,0	0,0	2,1
Tail Horizontal		14,0	98,0	13,7	0,3
Aluminium	67,5	9,5	98,0	9,3	0,2
TPC	30,0	4,2	98,0	4,1	0,1
Steel	2,5	0,4	98,0	0,3	0,0
Tail Vertical		4,0	98,0	3,9	0,1
Aluminium	70,0	2,8	98,0	2,7	0,1
TPC	30,0	1,2	98,0	1,2	0,0
Fuselage		107,0	94,6	101,2	5,8
Aluminium	88,0	94,2	98,0	92,3	1,9
Polycarbonates	5,8	6,2	93,1	5,8	0,4
Steel	3,0	3,2	98,0	3,1	0,1
Paint	3,2	3,4	0,0	0,0	3,4
Nacelle		12,0	98,0	11,8	0,2
Aluminium	100,0	12,0	98,0	11,8	0,2
Landing Gear		21,0	94,1	19,8	1,2
Aluminium	75,0	15,8	98,0	15,4	0,3
rubber	20,0	4,2	78,4	3,3	0,9
Steel	5,0	1,1	98,0	1,0	0,0
Engine		64,0	85,4	54,6	9,4
Fluids	5,0	3,2	93,1	3,0	0,2
Engine block	94,0	60,2	85,0	51,2	9,0
Rubber	1,0	0,6	78,4	0,5	0,1
Propeller		15,0	98,0	14,7	0,3
Wood	92,0	13,8	98,0	13,5	0,3
TPC	5,0	0,8	98,0	0,7	0,0
Steel	3,0	0,5	98,0	0,4	0,0
Fuel System		10,0	98,0	9,8	0,2
Aluminium	100,0	10,0	98,0	9,8	0,2
Flight Controls		12,0	98,0	11,8	0,2
Aluminium	100,0	12,0	98,0	11,8	0,2
Avionics		30,0	86,6	26,0	4,0
Electronics	60,0	18,0	85,6	15,4	2,6
Mech. Instr.	40,0	12,0	88,2	10,6	1,4
Electrical System		19,0	95,1	18,1	0,9
Lights	60,0	11,4	93,1	10,6	0,8
Wiring	40,0	7,6	98,0	7,4	0,2
Interior		34,0	98,0	33,3	0,7
	100,0	34,0	98,0	33,3	0,7
			Sum:	380,3	26,7
			[%] OEW:	93,4	6,6

Appendix I | Unit Cost Estimation

In this appendix, the Excel calculations for the unit cost estimation are shown.

Cost Source	Airplane program phases	Cost
Research, development, test and evaluation cost (C_RDTE)	Planning and Conceptual Design	$ 2,868,448
	Preliminary Design and System Integration	
	Detail Design and Development	
Acquisition cost (C_ACQ)	Manufacturing and Acquisition	$ 87,016,789
Operating cost (C_OPS)	Operation and Support	
Disassembly cost (C_DIS)	End-of-life	
Revenue from selling EOL materials (R_EOL)	End-of-life	$ 120,164
Total life cycle cost		**$ 89,885,237**
UNIT PRICE PER AIRPLANE		**$ 179,530**

Figure I.1: Overview of the estimation of the unit cost, Roskam method

Parameter	Symbol	Value	Comments
Engineering dollar rate per hour for entire program	R_e_m	50	May be assumed equal to R_e_r
Number of airplanes produced to production standard	N_m	500	
Total number of airplanes produced	N_program	502	
Cost per engine during manufacturing phase	C_e_m	11148	Appendix B , assume same as in RDTE
Cost per propellor during manufacturing phase	C_p_m	1088	Appendix B , assume same as in RDTE
Cost of avionics equipment per airplane	C_avionics_m	8250	Appendix C, assume same as in RDTE
Interior cost factor	F_int	500	500 USD/pax for light general aviation airplanes
Number of passengers	N_pax	2	
CEF 1990	CEF_1990	3.05	Page 20
Manufacturing labor rate in dollars per manhour	R_m_m	10	May be assumed equal to R_m_r
Airplane manfacturing rate in units per month	N_r_m	6	
Tooling labor rate in dollar manhour	R_t_m	10	
Airplane operating cost per hour	C_ops/hr	87	Lease cost estimation (wet lease - dry lease)
Number of flight test hours	t_pft	2	2 hours for general aviation
Overhead factor associated with flight tests	F_ftoh	4	Assume 4.0
Interest rate	F_fin_m	0.06	0.1-0.2
Required profit	F_pro_m	0.1	10% is common

Figure I.2: Overview of the input parameters for the acquisition cost

Parameter	Symbol	Value	Comments
Maximum speed	V_max	92.8	Cruise speed in KEAS (200 km/h TAS)
Number of airplanes produced for RDTE phase	N_rdte	2	2-8 for commercial programs
Complexity factor of new airplane program	F_diff	1	1.0 for conventional, 1.5 for mod. use of technology, 2.0 for adv. use of technology
Effect of CAD capability on design	F_cad	0.8	0.8 for experienced CAD users, 1.0 for manual drafting, 1.2 for CAD learners
Engineering dollar rate per hour	R_e_r	50	
Take-off weight	W_TO	1596	lbs, 724kg
Cost escalation factor (fig 2.7)	CEF	4.9	
Cost per engine	C_e_r	11148	Rotax 912ULS
Number of engines	N_e	1	818
Cost per propellor	C_p_r	1088	Based on reference prices for wooden propellers (W54EK)
Number of propellors	N_p	1	
Cost of avionics equipment per airplane	C_avionics_r	8250	Based on reference prices for avionic systems
Number of static test airplanes	N_st	2	ASSUMPTION
Manufacturing labor rate in dollars per manhour	R_m_r	10	
Correction factor for type of materials	F_mat	1	1.0 for conventional alu alloys, 1.5 for stainless steel, 2.0-2.5 for composites, 3.0 for carbon (AIRFRAME)
RDTE production rate in units per month	N_r_r	0.33	Typically 0.33
Tooling labor rate in dollar manhour	R_t_r	10	Figure 3.5, 97
Correction factor of having low observability	F_obs	1	1.0 for conventional (without stealth), 3.0 for stealthy airplanes
Correction factor of having extra facilities	F_tsf	0	
Required profit	F_pro_r	0.1	10% is common
Interest rate	F_fin_r	0.06	0.1-0.2

Figure I.3: Overview of the input parameters for the research, development, test and evaluation cost