Deliverable D 2.4

New recyclate materials with Life Cycle Impact Assessment

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Title	*New recyclate materials with Life Cycle Impact Assessment*	
Scope / purpose of deliverable	*This report consolidates results from the recycling assessment done by DELTA, of both thermoset CFRP and Aluminium substrate material equipped with a novel ZnO-based structural health monitoring system.* *For thermoset CFRP, this assessment was done via a physical recycling trial, using the common and established industrial recycling process for carbon thermoset material: the pyrolysis process.* *For Aluminium, the assessment was done based on theoretical data and common industry-standard practices.*	
Expected outcomes / contribution to impact	*Framework for performing high-level LCA of novel materials using recyclates*	
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23.10.2023	V1	*First draft with LCI results AIT and Invent*
08.12.2023	V2	*Second draft incl. Collins input, summary and introduction*
13.12.2023	V3	*LCI draft complete*
15.12.2023	V4	*LCA draft complete*
19.12.2023	V5	*Implemented AIT and Invent feedback*
22.12.2023	FINAL	*Final check and preparation for Upload*

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1 PUBLISHABLE SUMMARY

Improving sustainability is one of the key challenges of aviation. This includes reducing the waste of often high-quality, aeronautical grade materials. To solve this, SUSTAINair applies the 4R's of circular economy (redesign, repair, reuse, recycle) to the design, manufacturing, operations, and end-of-life of aircraft. In other words, SUSTAINair applies circular economy to the entire lifecycle of the aircraft.

More so then with conventional, linear economy (design, build, use and throw away) it can be difficult to accurately measure the sustainable performance of a circular system: Design choices made can have far reaching consequences throughout the lifecycle of an aircraft, prospective life cycle assessments for future aircraft (systems) are notoriously difficult and far from established, and common LCA approaches often don't include circular economy. This is a problem as you want to prevent making improvements for a single life cycle phase while negatively effecting the overall, lifecycle, performance.

Task 2.6 proposes a life cycle assessment (LCA) framework that assesses the sustainability performance of three novel production processes that are being developed in SUSTAINair. This task provides tools to objectively verify whether circular manufacturing positively effects overall sustainable performance over the lifecycle of an aircraft even when a lot of information is still unknown due to the experimental nature of SUSTAINair. All three processes that are assessed include some elements of circular economy (CE). The main goal of this deliverable is to provide a case study on how to integrate CE in an LCA framework in the context of aviation. It shows what data can be collected, how to account emissions prior or after the system that is assessed, and how to assess the impact of manufacturing on other life cycle phases.

2 INTRODUCTION

This document aims to propose a life cycle assessment (LCA) framework to assess the sustainability performance of three novel production processes that are being developed in SUSTAINair. All three processes include some elements of circular economy (CE). Whilst LCA's are an increasingly common tool to assess the sustainability impact of aerospace materials, parts or vehicles, the integration of CE is far from established. The main goal of this deliverable is to provide a case study on how to integrate CE in an LCA framework in the context of aviation.

Chapter 3 introduces and describes the methodology that is used in the study: LCA impact assessments, CE, and the hybrid CE-LCA model. Chapters 4 to 6 follow the template for LCA studies. Chapter 4 describes the goal and scope of the assessment including the choice for a functional unit. Chapter 5 gives an inventory of all known emissions and materials for the 3 production processes that are assessed. Chapter 6 discusses the life cycle impact of the 3 production processes. Finally, chapter 7 draws conclusions on the applicability and limitations of the approach developed for this assessment.

3 METHODOLOGY

3.1 Life Cycle Assessment

All parts, components, and products (e.g. an aircraft) require resources to be designed, produced, maintained, used and discarded. In addition they may rely on supporting infrastructure to function. What is being assessed is called the 'product system'. A life cycle assessment is a tool to measure the consumption of resources over the life of this product system.

How to perform a Life Cycle Assessment (LCA) is defined in the international standard **ISO 14044** (ISO, 2006). This standard provides requirements and guidelines for a well-structured and standardised assessment that can be compared to other studies.

According to the standard, each LCA consists of four distinct life 'phases':

1. The **goal and scope definition phase** – defines the system boundaries and level of detail that fit the goal of the study.
2. The **inventory analysis phase** – maps the performance of the system in the functional unit of choice per group (for example vehicle, infrastructure, or energy) and per life cycle component (for example production, operation, or end-of-life).
3. The **impact assessment phase** – connects all elements from the inventory analysis to assess the life cycle impact of the product or service that is being assessed.
4. The **interpretation phase** – gathers the results of the impact assessment, draws conclusions, and provides further recommendations.

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Note that a 'true' LCA includes the assessment phase (the 'A' in LCA). If the third impact assessment phase is excluded, the study is usually called a Life Cycle Inventory (LCI) assessment instead.

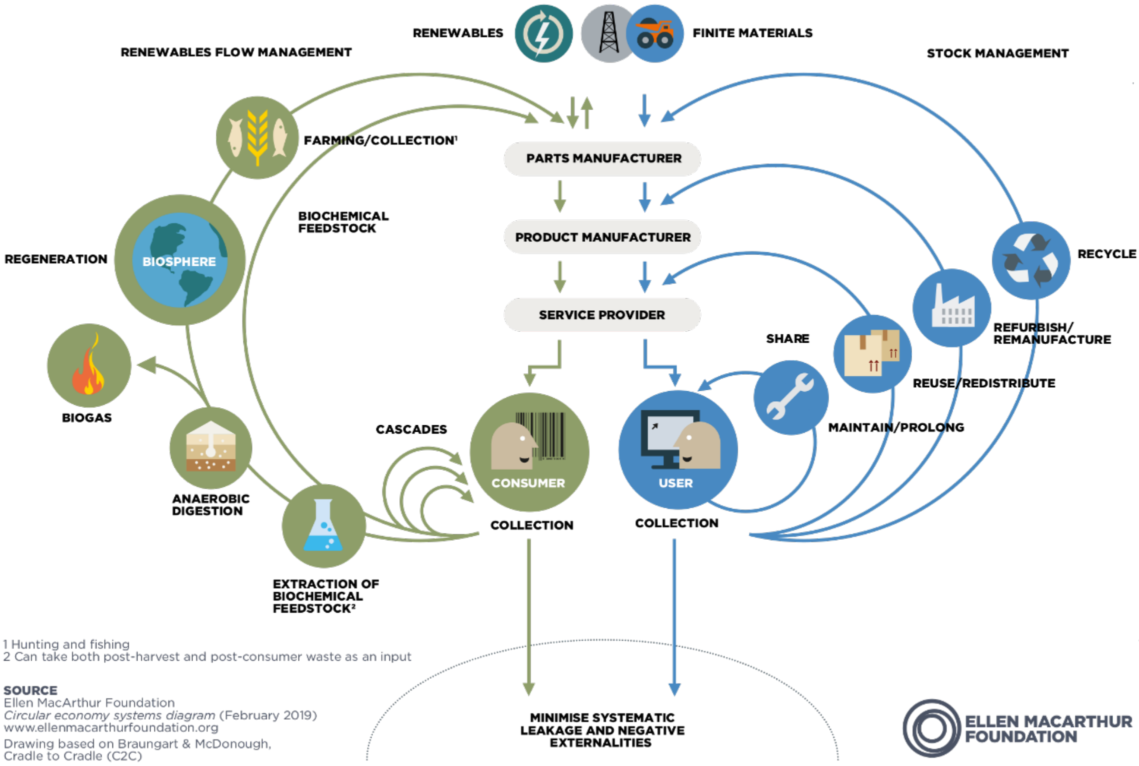
Depending on the intended use of the assessment, the scoping of the LCA can be adjusted to include only specific stages of a product system (e.g. only the use and maintenance of a part, but not production and end-of-life) or to set the boundaries of the product system itself (e.g. whether to include supporting infrastructure or not). Possible uses can be to compare the performance of different parts fulfilling similar missions or to assess the sustainable performance of a vehicle for accounting or optimization purposes.

Also depending on the intended use of the LCA, specific performance indicators can be chosen (e.g. cost, greenhouse gas emissions or use materials). The metric and unit that are used to assess the performance is called the 'functional unit' of the assessment. Possible functional units can be 'X' per passenger-km or 'Y' per kg of material or something else.

3.2 Circular Economy

Pearce & Turner define Circular Economy in their book 'Economics of Natural Resources and Environment' as an extension of the linear economic system based on production, goods, capital and utility or welfare. They argue that the linear system is limited as it does not include the natural environment which provides resources and acts as a 'waste-sink' and waste itself. Thus they define the CE system as a circular system that adds the natural environment and waste tot the conventional economic system (Pearce & Turner, 1990). The Ellen MacArthur Foundation defines CE as the opposite of the conventional, linear economy which takes resources, turns them into products and eventually throws them away. Instead is driven by three main principles: eliminate waste and pollution, circulate products and materials, and regenerate nature (Ellen MacArthur Foundation, N.D.).

The principles of CE can also be summarized using Value Retention Processes (VRPs) known as the 4 R's: **reduce** (the materials used), **repair** (when things break), **reuse** (materials that are no longer needed), and (as last resort) **recycle** (whatever material is left).



1 Hunting and fishing
2 Can take both post-harvest and post-consumer waste as an input

SOURCE
Ellen MacArthur Foundation
Circular economy systems diagram (February 2019)
www.ellenmacarthurfoundation.org
Drawing based on Braungart & McDonough,
Cradle to Cradle (C2C)

Figure 1: Butterfly model of CE (Ellen MacArthur Foundation, N.D.)

Aviation has already adopted some elements of CE such as a long service life (e.g. several decades) and design for repairability. However, other areas such as end-of-life solutions and recycling or reuse of materials have not been fully embraced yet. Whilst CE is practiced locally in some areas, aviation as a whole is still mostly linear: most circular solutions still have a low TRL and are not yet competitive (pricewise) with conventional, linear solutions. Also to truly capture the benefits of CE, it needs to be considered from the design phase on instead of being an afterthought (EREA, 2019).

3.3 CE-LCA model

The LCA have been identified as a useful tool to assess the sustainability of a product system. However, according to MacArthur LCA’s favour efficiency improvements over systemic change and are not designed with CE in mind (Ellen MacArthur Foundation, N.D.). Controversially, CE in itself does not automatically lead to social, economic or sustainable performance (Carpenter, 2022).

Circularity indicators for LCA’s can fill this gap. These complementary indicators can measure circularity of resources and material flows in LCA studies. Well-known indicators are the Material Circularity Indicator (MCI) and Linear Flow Indicator (LFI) by the Ellen MacArthur Foundation and the circular transition indicators (CTI) developed by the world business council for sustainable development (WBCSD) (Ingemarsdotter & Dumont, 2022).

An LCA model including CE is referred to as CE-LCA. The CE-LCA not only considers the ‘foreground system’, the product-system that is being assessed, but also any product-systems that provide recyclates to the foreground system or product-systems that receive material from the foreground system. These secondary product-systems make up the ‘extended-foreground system'. According to Walzberg (Walzberg, et al., 2021) a CE-LCA approach is well suited to assess the environmental impact of product or system at a product or supply chain level. It strengths are its ability to model the sustainability impact of technical processes, the systemic view it provides and that it can account for socio-economic impacts. It is however a static and data intensive method that is not capable to model market potential. An LCA is not the only tool to evaluate the sustainable performance of a product-system with CE elements. Other known assessment methods are Environmentally extended input output analysis (EEIOA), emergy/exergy analysis, system dynamics (SD) analysis, discrete event simulation (DES), agent-based modelling (ABM), operations research (OR), and finally material flow analysis (MFA).

Thus for the purpose of SUSTAINair however, a CE-LCA seems like a suitable approach to assess the sustainability of a circular product system.

3.4 Application in SUSTAINair

The sustainable performance of three production processes developed within SUSTAINair have been assessed using a CE-LCA model.

The assessment includes the four distinct life phases as described in ISO 14044-2006: goal and scope definition, inventory analysis, impact assessment and interpretation. The approach and results are described per phase in sections 4 to 7.

As the CE aspects in the three production processes that are assessed are limited to the use of recycled materials, a simple **cut-off approach** is selected to account for recyclates. The cut-off approach implies that the sustainable impact of the recycled material has already been accounted for. Thus, these materials can be used 'burden-free'.

The circularity of the material can be assessed using the aforementioned LFI value, which is determined as follows:

$$LFI = \frac{V + W}{2M}$$

Where:

V = mass of virgin material

W = amount of unrecoverable waste during production and end-of-life, but not the waste generated by the recycling process that provides the materials used in production as those are received 'burden-free'.

M = total material mass

Assessing the MCI is not possible without industry benchmarks on the materials usage and useful life.

Finally, it is assumed the carbon intensity of the electricity used in the production processes matches the national average of the factory's location. As shown below, the carbon intensity differs significantly among countries.

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Table 1: carbon intensity in 2022 (EEA, 2023)

PRODUCTION PROCESS	COUNTRY	CARBON INTENSITY (2022)
Flat plate thermoset	Germany	366 g CO_2e per kWh
Flat plate thermoplast	The Netherlands	321 g CO_2e per kWh
Diecast	Austria	96 g CO_2e per kWh
Reference	EU-27 average	251 g CO_2e per kWh

4 GOAL AND SCOPE

The goal of the assessment is to compare the life cycle impact of the parts or materials that are assessed with their conventional, linear counterparts. The parts will be assessed in terms of greenhouse gas (GHG) emissions and the functional unit will be 'per part' or 'per kg'.

The scoping in the assessment includes the following stages:

CE-A. Production, construction
CE-B. Use
CE-D. Disposal

Pre- and post-use of the materials is unknown and therefore excluded from the assessment.

As the assessed parts and production processes are still highly experimental and a lot of data is missing, the assessment will be mostly qualitative and relative to conventional production processes. The assessment of the use-stage will focus on the difference in weight at a component level, at least one level higher than the part itself that is being assessed and on a qualitative assessment of the impact on maintenance.

The three production processes that are assessed are shown in table 1 below.

Table 2: production processes to be assessed within T2.6

TASK	MATERIAL	PRODUCT	ASSSEMENT
T2.6.1 (Invent)	*Thermoset* composite	Flat plate	LCA
T2.6.2 (DTC)	*Thermoplast* composite	Laminate	LCA
T2.6.3 (AIT)	HPDC Al.	Fuselage part	Environmental impact assessment

5 LIFE CYCLE INVENTORY

This section lists all known emissions related to the three production processes including relevant emissions from the background system. All emissions are in g CO_2e per production batch, unless otherwise stated.

5.1 Thermoset flat plate LCI

For the 'thermoset' composite, waste material is used in a compression molding process to produce flat plates.

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The materials used include:

- Thermoset prepreg waste material
- Epoxy resin material
- Carbon fibres

The manufacturing processes include:

1. Cutting waste material with CNC cutter
2. Compression moulding process
3. Trimming of material

Circularity aspects:

- Use of recycled materials (received burden-free) instead of virgin material
- 30% of the electricity is produced using on-site solar panels

The tables below list all known inputs and outputs per production step. A carbon intensity of 366 g CO_2e per kWh in combination with 30% solar power is assumed.

Table 3: production step 1 'waste cutting' - inputs

INPUTS	AMOUNT
Virgin material	-
Recyclate material	320 g recycled waste material consisting of prepreg carbon fibre, prepreg epoxy and carbon fibre fabric
Energy	5.3 kWh

Table 4: production step 1 'waste cutting' - outputs

OUTPUTS	AMOUNT
Product	320 g cut flakes
Waste	-
Reusable waste	-
Emissions from energy	1,358 g CO_2e
Direct emissions to air	-
Emissions for waste treatment	-
Emissions from background system (e.g. virgin materials)	-

Table 5: production step 2 'compression molding' - inputs

INPUTS	**AMOUNT**
Material from previous step	320 g
Virgin material	-
Waste material	-
Energy	4.4 kWh

Table 6: production step 2 'compression molding' - outputs

OUTPUTS	**AMOUNT**
Product	316 g cured laminate plate
Waste	4 g
Reusable waste	-
Emissions from energy	1,127 g CO_2e
Direct emissions to air	-
Emissions for waste treatment	Unknown
Emissions from background system (e.g. virgin materials)	-

Table 7: production step 3 'trimming' - inputs

INPUTS	**AMOUNT**
Material from previous step	316 g
Virgin material	-
Waste material	-
Energy	0.106 kWh

Table 8: production step 3 'trimming' - outputs

OUTPUTS	**AMOUNT**
Product	304 g cured and trimmed laminate plates (or strips)
Waste	12 g
Reusable waste	-
Emissions from energy	27.2 g CO_2e
Direct emissions to air	-
Emissions for waste treatment	Unknown
Emissions from background system (e.g. virgin materials)	-

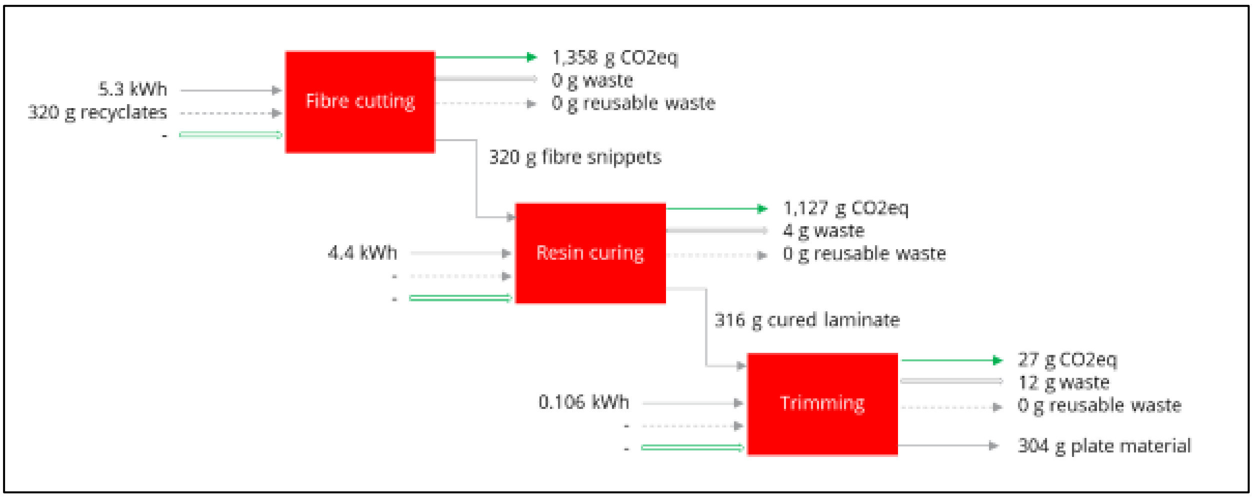

Figure 2: process overview of thermoset flat plate production

5.2 Thermoplast laminate material LCI

For the 'thermoplast' composite, shredded PPS waste material is used in a laminate material.

The materials used include:

- Polyphenylene sulphide (PPS) waste material

The manufacturing processes include the following steps:

1. Shredding of PPS waste material
2. Laminating process through consolidation
3. Forming of laminate
4. Trimming of laminate

Circularity aspects include:

- Use of recycled materials (received burden-free) instead of virgin material

Technical challenges include (as stated by DTC):

- Technical challenge: The PPS recyclate as DTC is currently processing into laminates, is courser than desired. This might present a challenge in laminate manufacturing. Unclear how this turns out for LM-PAEK recyclates.

The tables below list all known inputs and outputs per production step. A carbon intensity of 321 g CO$_2$e per kWh is assumed. Not all information could be retrieved in time, the emissions related to the use of virgin materials in the consolidation phase could not be determined.

Table 9: production step 1 'shredding' - inputs

INPUTS	AMOUNT
Virgin material	-
Recyclate material	20 kg recycled waste material consisting of material with carbon fibre and material with PPS resin
Energy	7.5 kWh

Table 10: production step 1 'shredding' - outputs

OUTPUTS	AMOUNT
Product	20 kg shredded flakes
Waste	-
Reusable waste	-
Emissions from energy	2,407.5 g CO_2e
Direct emissions to air	-
Emissions for waste treatment	-
Emissions from background system (e.g. virgin materials)	-

Table 11: production step 2 'consolidation' - inputs

INPUTS	AMOUNT
Material from previous step	3,010 g
Virgin material	990 g CF/PPS prepreg
Waste material	-
Energy	21 kWh

Table 12: production step 2 'consolidation' - outputs

OUTPUTS	AMOUNT
Product	4,000 g consolidated laminate
Waste	30 g burr material
Reusable waste	-
Emissions from energy	6,741 g CO_2e
Direct emissions to air	Resin material (background)
Emissions for waste treatment	Unknown
Emissions from background system (e.g. virgin materials)	Unknown

Table 13: production step 3 'forming' - inputs

INPUTS	AMOUNT
Material from previous step	333.3 g
Virgin material	-
Waste material	-
Energy	5 kWh

Table 14: production step 3 'forming' - outputs

OUTPUTS	AMOUNT
Product	333.3 g pressed laminate
Waste	-
Reusable waste	-
Emissions from energy	1,605 g CO_2e
Direct emissions to air	-
Emissions for waste treatment	-
Emissions from background system (e.g. virgin materials)	-

Table 15: production step 4 'trimming' - inputs

INPUTS	AMOUNT
Material from previous step	333.3 g
Virgin material	-
Waste material	-
Energy	0.425 kWh

Table 16: production step 4 'trimming' - outputs

OUTPUTS	AMOUNT
Product	300 g trimmed laminate
Waste	-
Reusable waste	33.3 g laminate scraps
Emissions from energy	136.4 g CO_2e
Emissions to air	-
Emissions for waste treatment	Unknown
Emissions from background system (e.g. virgin materials)	-

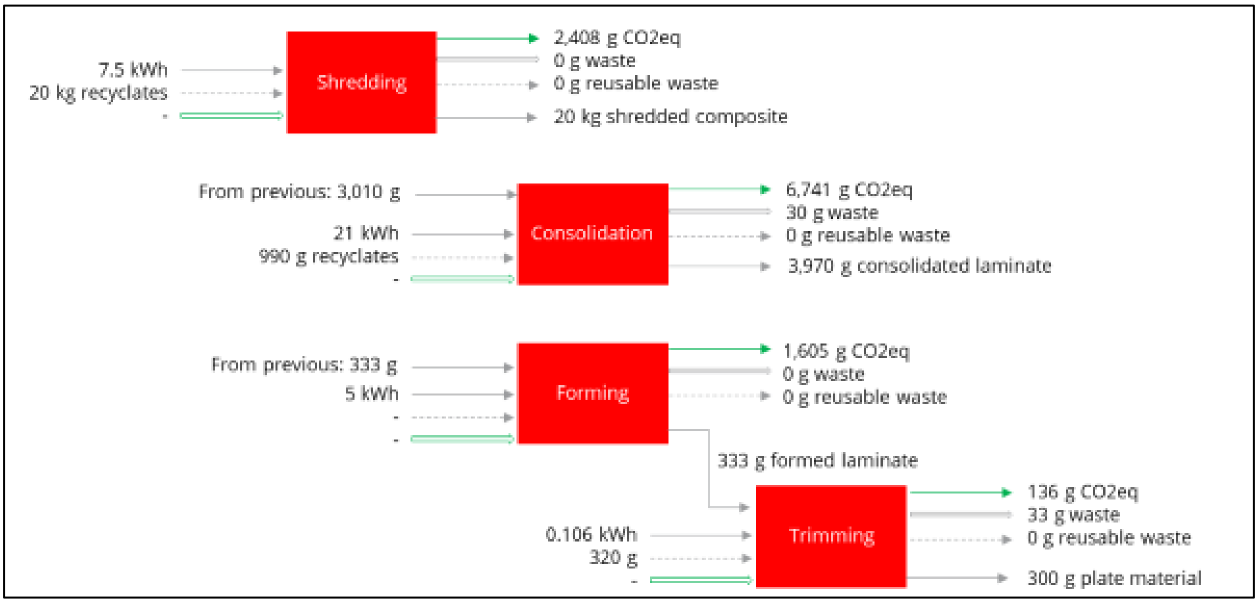

Figure 3: process overview of thermoplast laminate production. Note that batch size differs per production step!

5.3 Diecast aluminium part LCI

For the metal part, aluminium is casted in a die-cast mould instead of the more conventional milling process.

The materials used include:

- Aluminium 7075

The manufacturing processes include:

- Heating of the furnace
- High pressure diecast
- After treatments including heat treatments, quenching, artificial aging and milling

Circularity aspects include:

- Reduction of waste from production process
- Enables using lower grade materials

The tables below list all known inputs and outputs per production step. A carbon intensity of 96 g CO_2e per kWh is assumed.

Table 17: production step 1 'heating' - inputs

INPUTS	AMOUNT
Virgin material	2,973.6 g recycled aluminium alloy (assuming in-house recycling rate of 52.8%)
Waste material	3,326.4 g virgin aluminium alloy (Assuming in-house recycling rate of 52.8%)
Energy	0.249 kWh

Table 18: production step 1 'heating' - outputs

OUTPUTS	AMOUNT
Product	6,300 g preheated alloy
Waste	-
Reusable waste	-
Emissions from energy	23.9 g CO_2e
Emissions to air	-
Emissions for waste treatment	-
Emissions from background system (e.g. virgin materials)	34,432 g CO_2e from virgin aluminium alloy

Table 19: production step 2 'High Pressure diecast' - inputs

INPUTS	AMOUNT
Material from previous step	6,300 g
Virgin material	Tap water
Waste material	Wastewater
Energy	1,204 kWh

Table 20: production step 2 'High Pressure diecast' - outputs

OUTPUTS	AMOUNT
Product	6,000 g untreated diecast
Waste	-
Reusable waste	300 g
Emissions from energy	115.6 kg CO_2e
Emissions to air	-
Emissions from waste treatment	Unknown
Emissions from background system (e.g. virgin materials)	12.5 g CO_2e (wastewater and tap water)

Table 21: production step 3 'after treatments' - inputs

INPUTS	AMOUNT
Material from previous step	6,000 g
Virgin material	-
Waste material	-
Energy	63.8 kWh (quenching, heat treatment and aging, energy from milling is unknown but deemed very small)

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Table 22: production step 3 'after treatments' - outputs

OUTPUTS	AMOUNT
Product	3,220 g treated diecast
Waste	-
Reusable waste	2,780
Emissions from energy	6,125.9 g CO2e
Emissions to air	-
Emissions from waste treatment	-
Emissions from background system (e.g. virgin materials)	-

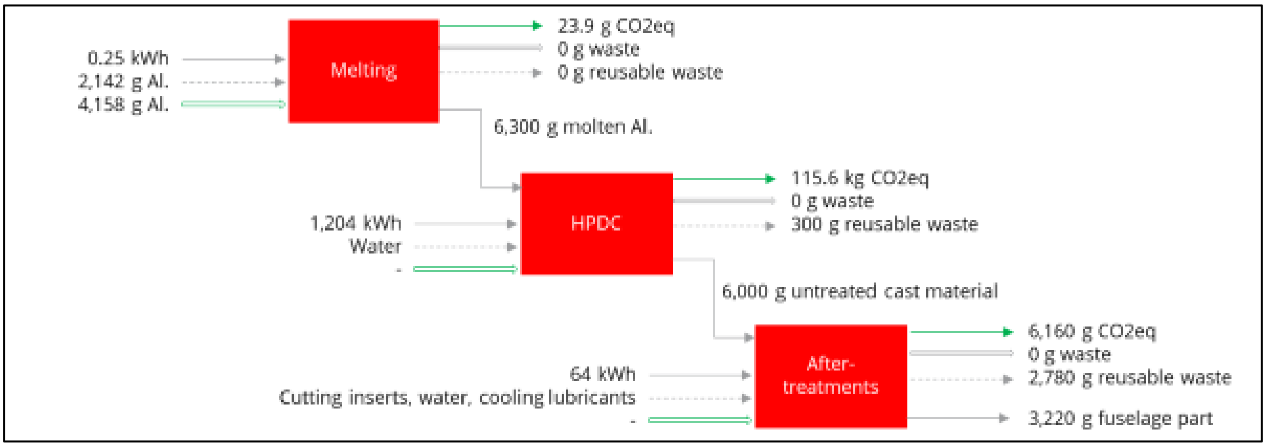

Figure 4: overview of diecast production

6 LIFE CYCLE ASSESSMENT

This section assesses the life cycle impact of the three productions processes that are assessed.

6.1 Thermoset flat plate LCA

6.1.1 Production

The production of the thermoset flat plate involves three sequential production steps. The batch sizes of the steps are aligned, thus all output of each step is used for the next. The resulting emissions and waste are listed below. Emissions related to the treatment of production waste could not be determined.

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Table 23: production emissions and waste for thermoset flat plate

MASS FINAL PRODUCT	EMISSIONS PER FINAL PRODUCT	WASTE PER FINAL PRODUCT	EMISSIONS PER KG PRODUCT	WASTE PER KG PRODUCT
304 g	2,512 g CO_2e	16 g (0% reusable)	8,264 g CO_2e	53 g (0% reusable)

6.1.2 Use phase

The plates can be used for coupon testing or joining experiments. Finding an aircraft application is part of the SUSTAINair research but is not yet considered in T2.6. The impact on weight or impact on maintainability can therefore not be foreseen and service life is still unknown.

6.1.3 End-of-life

According to Deliverable 2.1 thermoset composites can be recycled through either thermal, chemical, mechanical, or high voltage processes. Each process has its pros and cons. One of the main difficulties in thermoset recycling is to maintain the material properties of the recyclate. Conventional burning or grinding of the composites lead to the degradation or loss of the mechanical properties and an overall loss in financial value of the material. Chemical recycling relies on substances that can be harmful for the environment. Meanwhile, high voltage recycling is still highly experimental.

Thermal recycling through pyrolysis (at specific, controlled temperatures) are considered to be the most robust and scalable solution and were therefore further tested. It proved to be possible to recycle the material into useful product. The task focused on maintaining material properties; emissions during recycling were not given.

6.1.4 Impact of circularity

The thermoset flat plate uses low grade CF materials that otherwise would have been scrapped. All material inputs are recycled materials received burden free. This saves an unknown amount of CO2e compared to virgin materials. The production facility uses 30% renewable energy coming from solar.

The LFI is very much dependent on the assumptions related to the recycling efficiency of reusable waste and whether or not the product can be recycled or goes a landfill or incinerator as is shown below:

Table 24: Linear flow index of thermoset flat plate – weights per final product

RECYCLING EFFICIENCY AT EOL →	0%	70%	100%
Virgin material - V	0 g	0 g	0 g
Unrecoverable waste - W	320 g	107 g	16 g
Material mass - M	320 g	320 g	320 g
Linear flow index - LFI	**50 %**	**17%**	**3%**

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6.2 Thermoplast laminate LCA

6.2.1 Production

The production of the thermoplast laminate involves four sequential production steps. The batch sizes of the steps are not aligned, the output of one step is used for multiple batches of the next as shown below.

Table 25: material flow for production of the thermoplast laminate

	MATERIAL FROM PREVIOUS STEP	BATCH PRODUCT OUTPUT	BATCHES NEEDED FOR NEXT STEP	BATCHES NEEDED FOR 1 KG OF FINAL PRODUCT
Shredding	20 kg	20 kg	0.15	0.04
Consolidation	3,010 g	3,970 g	0.08	0.28
Forming	333 g	333 g	1	3.33
Trimming	333 g	300 g	-	3.33

The resulting emissions and waste are listed below. Emissions related to the treatment of production waste could not be determined.

Table 26: production emissions and waste for thermoset flat plate

MASS FINAL PRODUCT	EMISSIONS PER FINAL PRODUCT	WASTE PER FINAL PRODUCT	EMISSIONS PER KG PRODUCT	WASTE PER KG PRODUCT
300 g	2,338 g CO_2e	35.8 g	7,793 g CO_2e	119 g

6.2.2 Use phase

Also, for the thermoplast laminate, finding an aircraft application is part of the SUSTAINair research but is not yet considered in T2.6. The impact on weight or impact on maintainability can therefore not be foreseen and service life is still unknown.

6.2.3 End-of-life

Recycling of thermoplast composites was not assessed in D2.1.. In comparison to thermoset materials, thermoplasts are easier to recycle using thermal recycling as the material is easily reshaped and material properties are maintained under heat.

6.2.4 Impact of circularity

All material inputs are recycled materials received burden free. This saves an unknown amount of CO2e compared to virgin materials.

The LFI is very much dependent on the assumptions related to the recycling efficiency of reusable waste and whether or not the product can be recycled or goes a landfill or incinerator as is shown below:

Table 27: Linear flow index of thermoplast flat plate – weights per kg product

RECYCLING EFFICIENCY AT EOL →	0%	70%	100%
Virgin material - V	277 g	277 g	277 g
Unrecoverable waste - W	1,119 g	419 g	119 g
Material mass - M	1,119 g	1,119 g	1,119 g
Linear flow index - LFI	**62 %**	**31%**	**18%**

6.3 Diecast LCA

6.3.1 Production

The production of the thermoset flat plate involves three sequential production steps. The batch sizes of the steps are aligned, thus all output of each step is used for the next. The resulting emissions and waste are listed below. Emissions related to the treatment of production waste could not be determined.

Table 28: production emissions and waste for thermoset flat plate

PRODUCT MASS PER BATCH	EMISSIONS PER BATCH	WASTE PER BATCH	EMISSIONS PER KG PRODUCT	WASTE PER KG PRODUCT
3,220 g	156.2 kg CO_2e	3,080 g (reusable)	48.5 kg CO_2e	956.5 g (reusable)

6.3.2 Use phase

The aluminum diecast is part of a fuselage frame section. Compared to a conventional frame consisting of milled components, no changes in maintainability or service life are foreseen. Also weight is expected to be similar to the conventional reference part.

6.3.3 End-of-life

D2.1. also assesses recycling of aluminum materials. Aluminum is recycled through melting the material in a melting installation. Up to 2% contamination, the material can be recycled into aerospace grade materials. Up to 10% contamination, the material can be recycled into lower grade materials. The task focused on maintaining material properties; emissions during recycling were not given.

6.3.4 Impact of circularity

53% of material inputs are recycled materials received burden free. This saves approximately 38,500 g CO2e compared to using only virgin materials.

The LFI is very much dependent on the assumptions related to the recycling efficiency of reusable waste and whether or not the product can be recycled or goes a landfill or incinerator as is shown below:

Table 29: Linear flow index of thermoset flat plate – weights per final product

RECYCLING EFFICIENCY AT EOL →	0%	70%	100%
Virgin material - V	2,974 g	2,974 g	2,974 g
Unrecoverable waste - W	6,300 g	1,890 g	0 g
Material mass - M	6,300 g	6,300 g	6,300 g
Linear flow index - LFI	**74 %**	**31%**	**24%**

7 CONCLUSIONS

D2.4 provides a template on how to assess the life cycle impacts of materials and production processes using aspects of circular economy. The standard cut-of approach makes it straightforward to account for the use of recycled materials in the production process without the need to alter the basic LCA approach. The LCI value provides a usable indicator for the amount of circularity in the material. Even with the 3 materials mostly without an actual aircraft application it is possible to assess the sustainable life cycle impact. However, because little is known about the actual use phase and the recycling possibilities come end-of-life, the assessment is not complete.

Note however that the circularity involved in the three production processes and materials is relatively limited. When a more complex extended background system is involved with reuse of materials or parts in other systems that the accounting becomes more complex. A limitation of the cut-off approach is that reuse of materials at end-of-life do not lower the life cycle emissions. In fact, any emissions involved with the recycling are accounted to the foreground system and not to the receiving background system. This goes both ways however as recyclate materials that are received are received 'burden-free', thus any emissions involved with readying these materials for their new application is not accounted to the receiving foreground system but to the background system.

Without a proper assessment of the use phase and the weight impact at the higher system level, it is not possible to determine the net impact on sustainability. If savings during production, maintenance or end-of-life were to increase the weight and as a result the emissions during the use phase, it is likely that the net effect on sustainability is negative. This is something to take into account with aircraft- and other light weight materials.