Environmental grading of materials as an ECO-DESIGN tool

Louison BERNARDI

School of Science

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Supervisors

Mathias Groth

Elina Kähkönen

Advisor

Nicolas Mistou

Aalto University
School of Science

Aalto University, P.O. BOX 11000, 00076 AALTO
www.aalto.fi
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Author Louison Bernardi

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Abstract

The main goal of this master thesis is to develop an Eco-design tool for the aeronautical sectors comparing the traditional aeronautical materials (aluminium vs carbon composite). This Eco-design tool assesses the environmental performance of materials into grades and those grades are implement in traditional design tool. The environmental grades are determined using a life cycle assessment (LCA) approach. The method used to answer those question is: i. performing an environmental assessment of the selected materials, ii. translating the environmental assessment into grades and iii. evaluating the LCA uncertainties of the obtained grade thanks to characterization and numerical simulations.

First, the comparison of materials environmental impacts during the design process relies on environmental assessment of materials. This environmental assessment is performed using the LCA method and the LCA software GaBi. The scope on the LCA is limited to the manufacturing of the final materials from virgin and (if possible) secondary materials. The impact assessment methods used are ReCiPe 2016 and Environmental Footprint 2.0. The environmental assessment gives the environmental impacts on 16 impacts categories including acidification, human toxicity, climate change or energy resource. The raw results of the conducted LCA are not on an easy-accessible format and that is the reason why the LCA results are transformed into environmental grades.

Thus, the impacts of a material are translated into grade by normalizing the environmental assessment results and a weighting method. The normalization allows to make the different impacts dimensionless and thus be able to combine the different impact into a grade. The weighting method provides weighting factors for each impact category and allows to obtain the final environmental grade. The weighting factors represent the importance of each impact category, these factors were determined by Castenalli (Castellani et al., 2016).

Finally, the uncertainties are determined by applying standard deviation analysis to the critical parameters and Monte Carlo simulations.

Keywords Aeronautical materials, Environmental assessment, Life cycle assessment, Eco-design, Environmental grade

Preface

First, I want to thank all the persons that made this internship possible. I want to thank my advisor Nicolas Mistou who brought me insightful guidance and helped me being at ease at Expleo. I also want to thank my supervisors Mathias Groth and Elina Kähkönen who helped me sticking with the time schedule. Elina also helped me a lot with the structural part of my thesis and gave me LCA expert guidance. Mathias helped me put things into perspectives and make this thesis understandable for non-LCA experts.

I am also glad of the trust and responsibilities Expleo gave me during this coronavirus pandemic. Indeed, thanks to it, I was able to continue my thesis work remotely, as if I was at the company.

Finally, I am thankful for all the people I met during this thesis who made the work place a cheerful and stimulated place.

Toulouse, 03.7.2020

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Table of content

Preface 5

Symbols and abbreviations 7

I. INTRODUCTION 9

II. THEORY PART 10

  1. Corporate social responsibility: general definition 10

  2. Economic Responsibilities: Expleo and the aeronautical industry. 11

  3. Legal Responsibilities: aeronautical regulations and CSR reporting 13

  4. Ethical Responsibilities: guidance towards sustainability 14

    1. LCA 15

    2. GaBi (Thinkstep, 2012) 21

III. RESEARCH PART 25

  1. Methods 25

    1. Environmental assessment 25

    2. Grading system 28

    3. Evaluation of uncertainties 29

  2. Results 31

    1. Environmental assessment 31

    2. Grading system 38

    3. Evaluation of uncertainties 39

IV. CONCLUSION 40

References 42

Appendix A: Carbon fibers chemical reaction 46

Appendix B: Plan created on GaBi 47

  I. Aluminium alloy 2024 47

  II. Aluminium alloy 7175 49

  III. Carbon/epoxy composite 51

Appendix C: Normalized environmental impacts with Environmental Footprint 2.0 53

Appendix D: Evaluation of uncertainties 54

  I. Aluminium alloy 2024 54

  II. Aluminium alloy 7175 55

  III. Carbon composite 56

Symbols and abbreviations

Symbols

$\boldsymbol{Wf_i}$	the weighting factor associated to the i impact category
$\boldsymbol{Nf_i}$	the normalization factor associated to the i impact category
$\boldsymbol{IC_i(material)}$	the results on the i impact category of the material
$\boldsymbol{grade_i(material)}$	the subgrade associated to the i impact category of the material
$\boldsymbol{IC_i}$	stands for the impact category i
$\boldsymbol{\sigma_{IC_i}}$	the standard deviation obtained for this impact category i during Monte Carlo simulations
$\boldsymbol{n}$	the number of simulations runs
$\boldsymbol{u_{IC_i}(material)}$	the uncertainty for IC_i of the material
$\boldsymbol{u_{Nf_i}}$	the uncertainty of the normalization factor
$\boldsymbol{u_{Wf_i}}$	the uncertainty of the weighting factor
$\boldsymbol{u_{grade_i}(material)}$	the uncertainty for $grade_i$ of the material
$\boldsymbol{u_{GRADE}(material)}$	the uncertainty for the final grade of the material

Operators

$\sum_{\boldsymbol{i\ the\ IC}}$	sum over i the impact categories

Abbreviations

LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
CSR	Corporate Social Responsibilities
R&D	Research and Development
BU	Business Unit
REACH	Regulation, Evaluation and Authorization of Chemicals Hazardous substances
RoHS	Restriction of Hazardous Substances

EPD	Environmental Product Declaration
PCR	Product Category Rule
IPCC	International Panel on Climate Change

I. INTRODUCTION

The aim of this work is to develop a tool for Eco-Design in aeronautics. The general idea is to give environmental grades to materials. Ideally, the grades would be useful when conceiving a product and it would help choosing a material with a lower environmental impact. This adds an environmental aspect to the traditional product design leading to an eco-design approach.

The environmental grades are determined using a Life Cycle Assessment (LCA) approach using the LCA software GaBi. Only the extraction of raw materials, the processing of raw materials into desired materials and the valorization of materials have been considered for these environmental grades. This choice relies on the idea that the environmental grades can be used independent of the final product application. The limitations of this grading system are also taken into account including the data quality, the results liability and uncertainties are studied.

In the present study, notion of “corporate social responsibility applied to the aeronautics” and Expleo will be presented first. Secondly, a more detailed description of the environmental assessment method used during this study will be introduced: the Life Cycle Assessment (LCA) method and the LCA software GaBi. Thirdly, the core of this work will be described: the environmental grading method and the uncertainties evaluation of the grading system. Finally, a discussion and conclusion of the results will be conducted.

II. THEORY PART

1. Corporate social responsibility: general definition

Companies have always had impact on their environment. Corporate Social Responsibility (CSR) is a global concept that aims at a flourishing company economy while preserving employee wellness and environmental resources. CSR can be seen as a "win-win" situation for companies and societies in general (Jysmä, 2014).

CSR is not a new concept. The first mention of CSR dates back to the 1950s according to several authors (Jysmä, 2014). From the 1950s until now, the same general idea of CSR is that companies are not only businesses with legal obligations but also true actors of their environments (Jysmä, 2014).

In practice, CSR can be translated into companies as the development and implementation of sustainable strategies. A sustainable strategy can be described as strategy that meets the present's needs without infringing with the future's needs. (Assembly, February 2009) Sustainability relies on three pillars: social, economic and environmental also known as the "3P" for people, profit and planet. (Fig. 1) Thus, in other words, a sustainable development is a development that creates benefices while preserving ecosystems and humans.

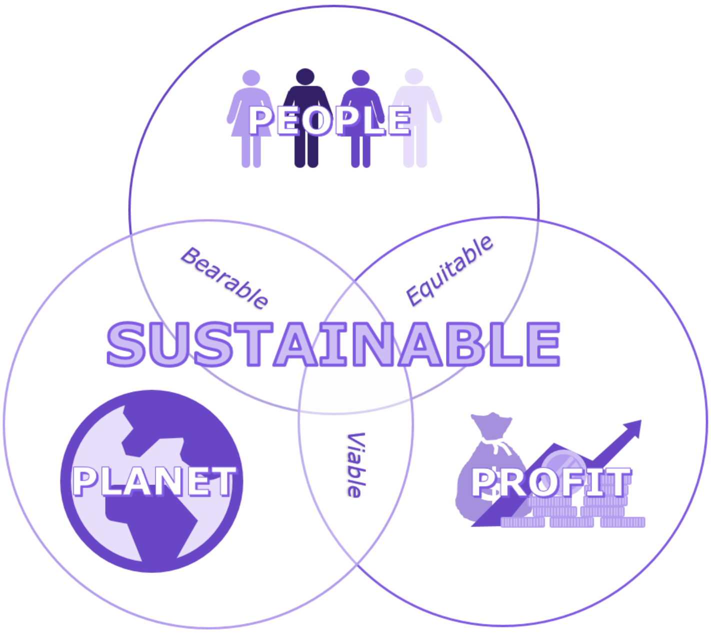


Figure 1 - Concept of sustainability (drawing inspired by (ecology, 2020))

One commonly used approach in CSR is Carroll's pyramid: economic, legal, ethical and philanthropic aspirations(Carroll, 2016). The economic responsibilities are at the base of the pyramid since the economic is the very foundation of each company. Closely followed by the legal ones, each company must abide by laws and regulations. Then the ethical ones, each company must be an ethic model. Finally, the philanthropic ones, society expects that companies give in return. (Maon et al., 2017). The last layer of the Carroll's pyramid is out of the scope of this thesis. An adapted Carroll's pyramid (Fig. 2) can structure the present theory part. Indeed, Eco design is an ethical approach of a classical design.

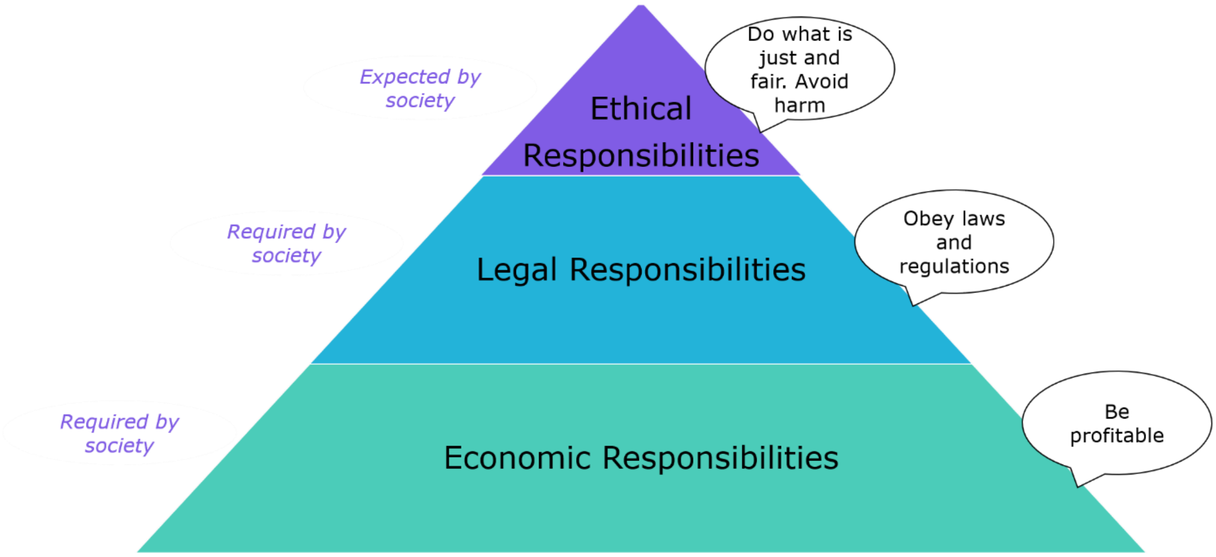


Figure 2 - Adapted Carroll's pyramid (Carroll, 2016)

2. Economic Responsibilities: Expleo and the aeronautical industry.

Expleo group is an engineering consulting company. Its former name is Assystem Technologies; it used to be the R&D division of Assystem, and it became an independent company in 2007.

Expleo group covers the full life cycle with end-to-end integrated solutions for other industrial companies. Expleo group offers consulting, engineering and quality services. The group employs more than 15,000 employees in over 30 countries. It generated around 1,1 bn euro in revenue in 2019. Expleo group is acting on several technological sectors including aeronautics, automotive, space and defense. (Expleo, 2020)

The present thesis took place at Expleo Toulouse. Expleo Toulouse is located is the South of France and employs about 2,100 employees.

The Toulouse Expleo site works on several industries, including aeronautics, defense, space or automobile. Aeronautical application represents a high majority of Expleo Toulouse activities. Airbus is one of the most important clients of Expleo Toulouse: Airbus contracts represent roughly 80% of the Expleo Toulouse activities. Expleo provides services from designing aerospace parts to managing final assembly line.

Aeronautical industry encompasses a wide range of activities, including aeronautical parts design, production, maintenance and end-of life. This business is shared by two major actors for civil aircrafts: Airbus and Boeing. (Comission, Aeronautics industries, 2020)

Expleo Toulouse counts several Business Unit (BU), which are Engineering, Engineering and Manufacturing, System Engineering and Customers Supports. Each BU offers different expertise divisions. The thesis was developed by the Engineering and Manufacturing BU (Fig. 3) at the Research division.

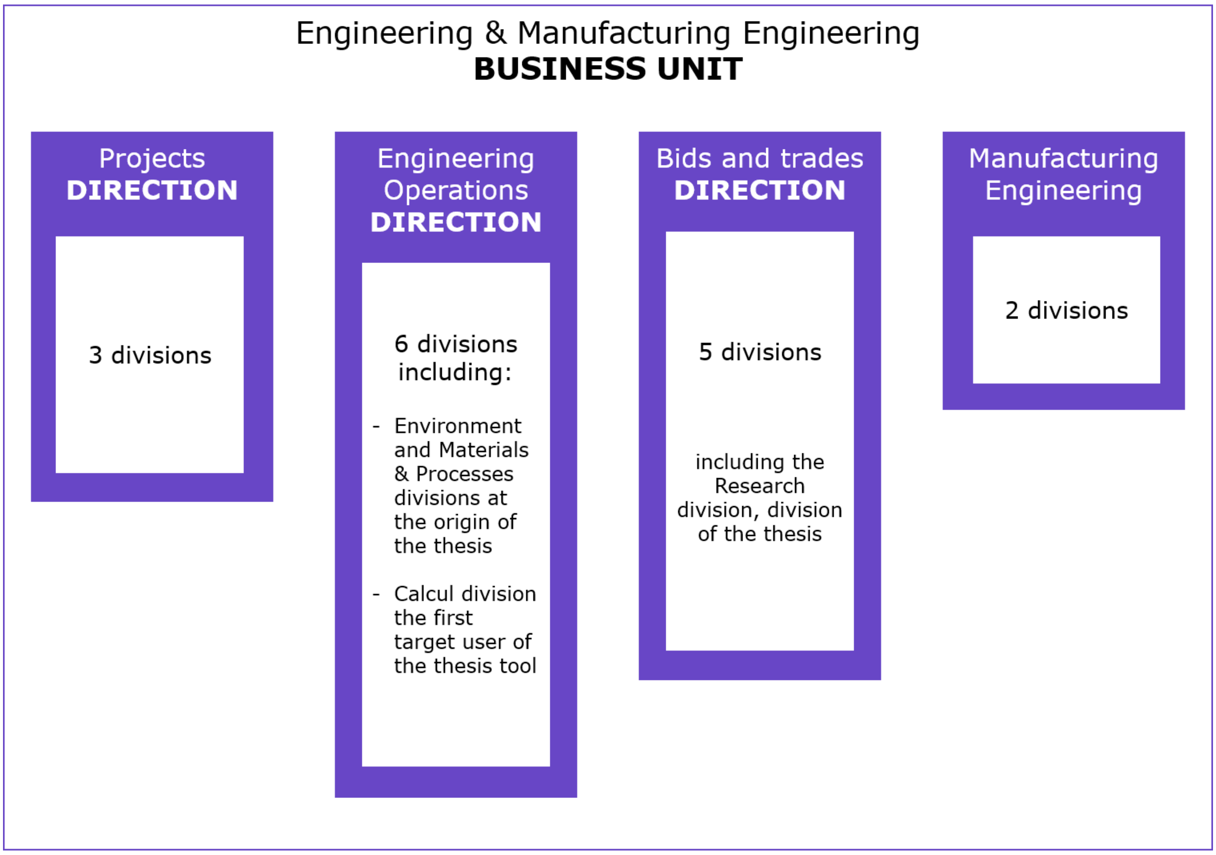


Figure 3 - Expleo Engineering & Manufacturing Engineering Business Unit

The Calcul Engineering Operation of Expleo models aerospace parts for Airbus. When modelling an aerospace piece, this division needs to include technical requirements, mechanical specification and optimize material weight. Piece design needs to meet robustness and resistance requirements to ensure the usability of the piece for an aimed application. One of the central properties during the development process is weight optimization: it ensures the cost feasibility of the piece during the use phase. In order to optimize airplane weight, the materials used must be both light and mechanically resistant. The most used materials for airplanes are aluminium alloys, titan alloys and composites. (Aliaga,D. & al, 2014)

Designing a product or a service means finding a solution to a customers' need. It relies on three criteria: technical feasibility, customers' requirements and cost management (Fig. 4).

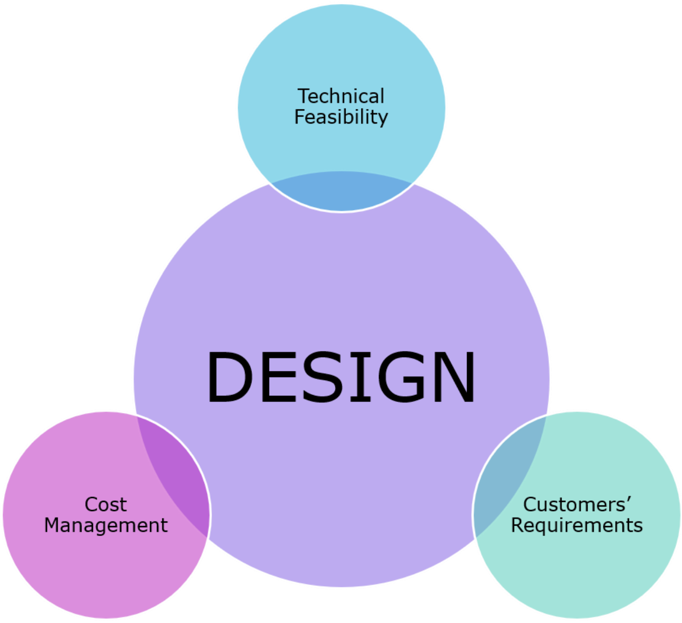


Figure 4 – Design (Hauptstrasse, 2018)

For now, the Calcul Engineering Operation designs aerospace using classical design method. The final goal of this study is to add an environmental approach to the current design method, leading to an eco-design approach (Fig. 5). The environmental grade is determined in function of a material quantity. The designed parts can then get a total environmental score.

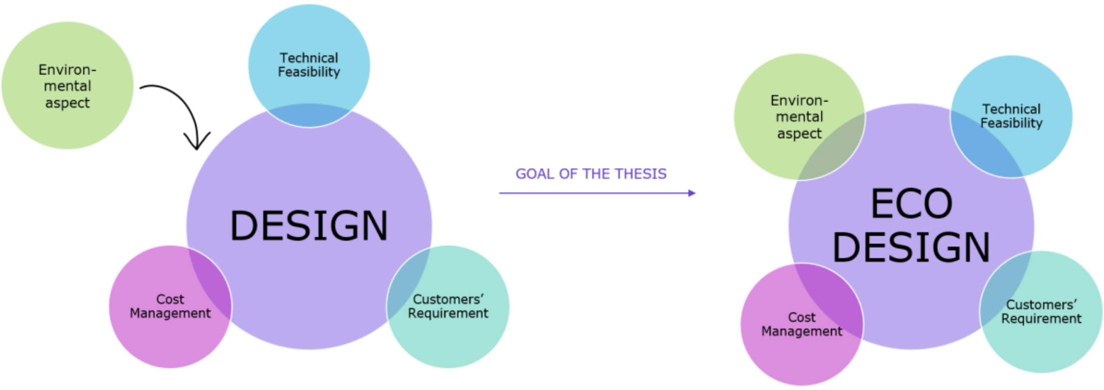


Figure 5 - Eco Design (Hauptstrasse, 2018)

3. Legal Responsibilities: aeronautical regulations and CSR reporting

Aeronautical industry is strictly regulated. The regulations extend from safety measures to environmental regulation. The critical regulations in our case are the environmental ones, related to emissions, materials and sustainable reporting.

The European Commission set up legislations for preserving air quality: The Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 guides ambient air quality and cleaner air for Europe (Parliament et al., 2008). This directive focuses on limiting carbon dioxide (CO2), nitrogen oxide (NOx), volatile organic compounds and particulate emissions. It is a common directive to all industries and not only for aeronautics. (Comission, Air quality, 2020)

As for materials, the European Union set up the REACH regulation and the RoHS directive; standing for Regulation, Evaluation and Authorization of Chemicals Hazardous substances and Restriction of Hazardous Substances, respectively.

REACH was adopted to improve human health and preserve ecosystems by reducing the number of chemical hazardous substances on the market. REACH can authorize, restrict or ban chemical hazardous substances. It is applicable to the Europe Economics Aera (European Union + Norway, Iceland and Lichtenstein) (Comission, REACH, 2020). REACH establishes different kinds of substance lists: the registered substances, the candidate list substances, the restricted substances and the banned substances. The different lists of substances are constantly evolving through time. The candidate list substances are substances still under deliberation with a very high concern, manufacturers have to communicate about the weight percentage of those substances in their products. Restricted substances cannot be produced in the European Economic Area (EEA) however they can be present or used during manufacturing imported products. Banned substances cannot be produced in the EEA nor be present or used during manufacturing imported products. REACH affects both substance manufacturers, importers of substances and downstream user. (Expleo Toulouse, REACH,2020.) RoHS limits the use of hazardous substances including lead, mercury, cadmium or hexavalent chromium. RoHS establishes a maximum permitted concentration in separated parts of a product for these hazardous substances. (EC 2008)

Materials are subjected to REACH regulation and RoHS directive. In general, alloys are more concerned by REACH than composites. (Aliaga,D. & al, 2014).

CSR reporting is an EU law that obliges large companies to disclose non-financial reporting. European large companies must abide by the European legislation on environmental and societal issues but also be innovative and set up environmental and societal actions. Those environmental and societal actions must be reported in the CSR report. Large company is defined as a company with more than 500 employees (Comission, Company reporting and auditing, 2020). Expleo, the company case study, must abide by this law since it is considered as a large company (more than 15,000 employees i.e. I.3).

4. Ethical Responsibilities: guidance towards sustainability

There are voluntary guidances towards sustainability such as: environmental management ISO 14001 standards, sustainable reporting according to Global Reporting Initiative (GRI) guidelines or Atlantic Interoperability Initiative to Reduce Emissions (AIRE) (Comission, Air, 2020)

The study case company, Expleo, is currently getting the ISO 14001 certification (ISO14001, 2020), an environmental management certification, and wants to assert its will in the environmental transition. The ISO 14001 certification is a true asset which can be a game changer to solicit bids.

Expleo also aims at developing offers related to sustainable issues. To do so, Expleo develops its range of expertise: it aims to be qualified in Eco-Design. This Masters' thesis was designed along this intent. An eco-design is a design that integrates an environmental aspect (Fig. 5). Eco-design aims at creating a product meeting the customer's need while being more eco-friendly. The two classical steps of eco-design approach are environmental assessment and environmental improvement. (Vallet et al., 2013)

The first step gives the environmental performance of an existing product/service while the second step aims to find strategies and solutions to lower the environmental impact of a product. Since the present study focuses on a part of a product materials, only environmental assessment of eco-design is dealt. The aim is to develop an applicable material choosing tool for the design process. The tool should be reliable and simple. There are simplified tools for making product comparison, including carbon footprint (Carbon Footprint, 2020). However, these tools exclude many of the environmental impact. For instance, carbon footprint focuses solely on the greenhouse gas emissions (Carbon Footprint, 2020).

The holistic way to determine environmental assessment is by using the Life Cycle Assessment (LCA) method.

1. LCA

LCA is a way to assess the environmental impact of a product through its life cycle (Fig. 6). (Valenciennes, s.d.) Commonly, the different life cycle phases are the following (Valenciennes, s.d.):

- Raw materials: extraction of the raw materials.
- Materials: process transforming raw materials into materials.
- Manufacturing: assembly of different materials creating the final product.
- Transportation: transportation of the product from the manufacturing site to the distribution place.
- Use phase.
- End of life: some parts of the product are thrown away.
- Valorization: some parts of the product are recycled or used for creating energy (ADEME, 2020).

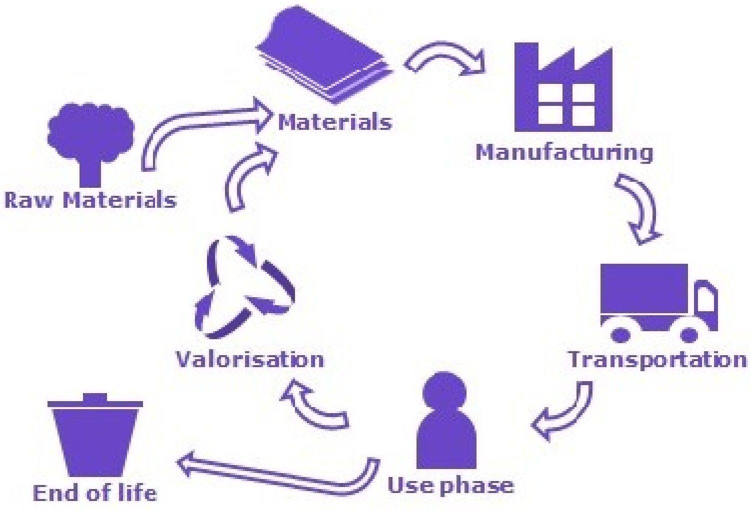


Figure 6 - Life Cycle (drawing modified from (ADEME, 2020))

For each phase of the life cycle, input (energy, materials) and output (energy, products, emissions, waste, by-product) flows are listed. (ADEME, 2020) Due to impact assessment method, potential impacts and damages caused by those flows are determined on different impact categories. The most commonly used impact category is the climate change potential, other impact categories relate to human health, ecosystems or resources such as Eutrophication or Ionizing radiation. (Valenciennes, s.d.) The different impact categories are described in more details further in this section. The analysis of those impacts allows determining environmental areas of improvement. LCA aims at including all relevant impacts associated with the product. It is used for information on a product, determination of environmental areas of improvements, indicators of environmental performance or green marketing (AFNOR, ISO 14044: Environmental management - Life cycle assessment - Requirements and guidelines - Amendment 1, 2018). The study uses LCA for developing an applicable tool for material choices in product design process.

LCA provides information on environmental performance of a product and determining the environmental areas of improvement. The LCA results are useful for sustainable marketing campaign; a brand can claim the environmental performance of its product thanks to LCA (AFNOR, ISO 14040: Environmental management - Life cycle assessment - Principles and framework, 2006) through Environmental Product Declaration (EPD). (*Declaration environnementale*, n.d.) An EPD allows to compare several products with a same function. An EPD report is governed by a Product Category Rule (PCR). PCR is standardized method regulated by the ISO 14024. The PCR defines how to conduct the LCA and reports the result inside an EPD (*Declaration environnementale*, n.d.)

LCA is a normalized method: the standards ISO 14040 and 14044 give the set up for LCA practitioners. (AFNOR, ISO 14040: Environmental management - Life cycle assessment - Principles and framework, 2006) (AFNOR, ISO 14044: Environmental management - Life cycle assessment - Requirements and guidelines - Amendment 1, 2018). According to the ISO standards, an LCA study relies on four steps: i. definition of the goal and scope of the study, ii. life cycle inventory (LCI), iii. life cycle impact assessment (LCIA) and iv. interpretation of the results.

i. Goal and scope definition

The goal and scope of the LCA study must be defined clearly in the first step. The goal must state the intended application, the audience and the type of report (e.g., comparative report or not). The scope mainly consists in defining the product system, the functional unit, the system boundary, the impact assessment method and the impacts. The functional unit represents the functionality of the studied product or service of the LCA. Each choice must be justified.

ii. Life-cycle inventory (LCI)

The LCI step consists in collecting all the input and output data for each process of the product. Data are raw material input, energy, physical, substance input or output, product, co-product, waste and emission to air, soil or water. Figure 7 outlines the LCI step. Collected data are either measured, calculated or estimated. (AFNOR, ISO 14044: Environmental management - Life cycle assessment - Requirements and guidelines - Amendment 1, 2018)

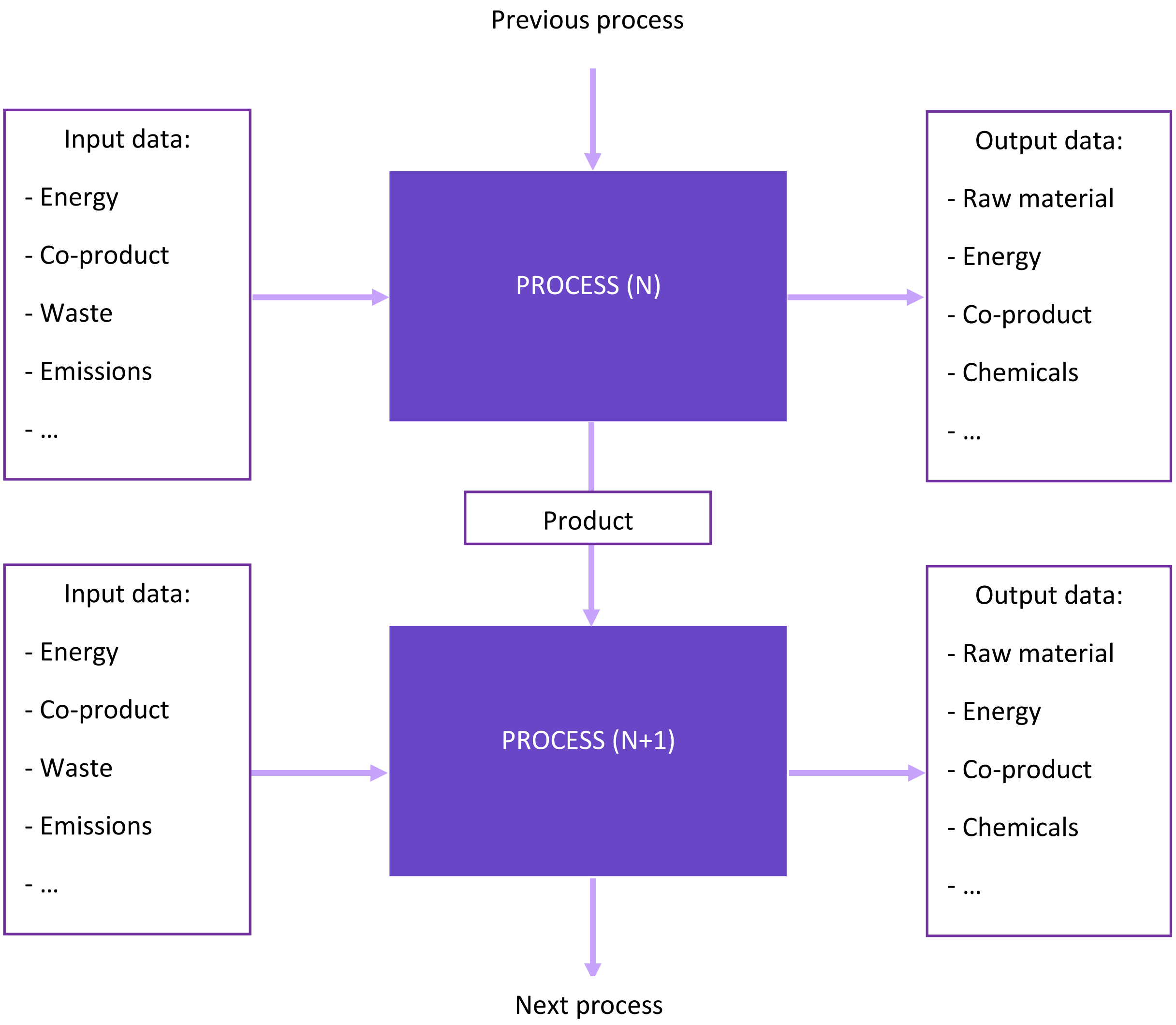


Figure 7 - Data and process

iii. Life-cycle impact assessment (LCIA)

The LCIA step characterizes the impact of LCI on the following impact categories: acidification, human toxicity (cancer), climate change, eutrophication freshwater, eutrophication terrestrial, ionizing radiation, land use, human toxicity (non-cancer), ozone depletion, photochemical ozone formation, resource depletion fossils, resource depletion mineral, particulate matter, ecotoxicity freshwater, resource depletion water. (Fig. 8, table 1) This characterization reflects the characterization factors as they assess the potential impact of a substance used during the life cycle of the product on impact categories. The methodologies are either midpoint or damage oriented. Midpoint categories characterize direct impact on the early stage of the cause-effect chain while damage categories characterize potential impact at a damage level (i.e. at the end of the cause-effect chain). (Goedkoop et al, 2009) Each category is expressed in specific unity; usually impact categories are expressed in function of a reference substance (climate change: kg CO2 eq). For instance, the climate change category characterization is determined by the International Panel on Climate Change (IPCC), a group of scientific experts. The IPCC establishes the impact on climate change for each substance and translates it into a kilogram equivalent of carbon dioxide thanks to characterization factors. (IPCC, 2020)

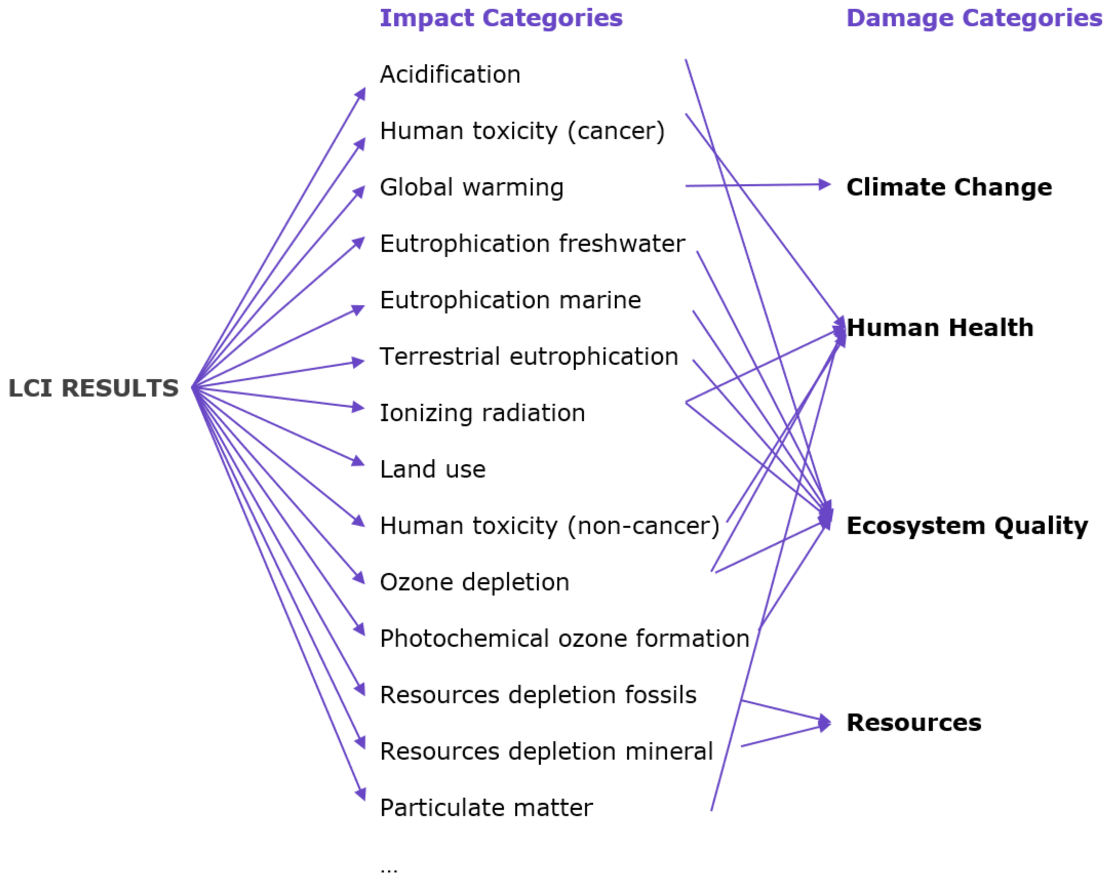


Figure 8 – Impact and Damage categories

The impact assessment, which are also called characterization methods, are scientific based and approved by the international communities of LCA practitioners. From one method to another, there are some discrepancies. (ESU services, 2019) The impact assessment method must be chosen carefully according to the study and the impact categories chosen.

The two LCIA methods chosen for this study are ReCiPe 2016 and Environmental Footprint 2.0. They rely on scientific findings approved by LCA community. (ESU services, 2019) ReCiPe 2016 is a hybrid method and Environmental Footprint is a classical impact method. (ESU services, 2019) N. Thériault conducted a paper research in 2010 about different LCIA methods comparing the liability over several criteria of characterization methods for each environmental category impact. The ReCiPe method appeared to be slightly more reliable than other methods on a higher number of category impacts. (Thériault, 2011) The Environmental Footprint method, it is constructed by the European Environmental Footprint initiative (Comission, Environmental Footprint, 2020). This method is designed specifically for Europe and recommended according to the International Life Cycle Data Handbook (ILCD) (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010).

Table 1 gives a physical description of some impact categories and their unity in function of the impact assessment method.

Table 1 - Description of Impact Categories (National Institute for Public Health and the Environment - Ministry of Health, 2016)(Tobergte & Curtis, 2013)

Impact category	Unit		Description
	ReCiPe v1.08	Environmental Footprint 2.0	
Acidification	kg SO2	mole H+	Terrestrial acidification is caused by deposition of inorganic substances such as sulphates, nitrates and phosphates. The change in acidity infringes ecosystems. The reference substances are acid substances.
Human toxicity	kg 1,4-DCB	CTUh	Chemical exposure can have negative impact on human lives. Human toxicity evaluates the damage of chemical pollutant on human. Unities are either expressed according to a reference substance or a created unit. The reference substance 1,4-Dichlorobenzene (1,4 – DCB) is a substance with a high environmental and human toxicity. The created unity CTUh stands for Comparative Toxic Unit for human.
Climate change	kg CO2	kg CO2	Climate change refers to the increase of the average temperature on Earth. This increase is mainly due to an increase of greenhouse gases (CO2, CH4 …) in the atmosphere. The reference substance (i.e. the unit) for this impact category is the dioxide carbon which is a very common greenhouse gas.
Freshwater eutrophication	kg P	kg P	The excess of nutrients into freshwater leads to a freshwater eutrophication. Freshwater eutrophication induces an increase of algae of specific microorganisms leading to a loss of biodiversity. The reference substance is phosphate because in freshwater it is the main element held responsible for the eutrophication phenomenon.
Marine eutrophication	kg N	kg N	The excess of nutrients into marine water leads to a marine eutrophication. Marine eutrophication induces an oxygen depletion in water leading to a loss of marine ecosystems. The reference substance is azote because in marine water it is the main element held responsible for the eutrophication phenomenon.
Terrestrial ecotoxicity / Eutrophication terrestrial	kg to 1,4-DCB	mole of N	Chemical exposure can have negative impact on ecosystems. Terrestrial toxicity evaluates the damage of chemical pollutant on soils. The reference substances are 1,4 DCB which is a substance with a high environmental toxicity and azote (N) which create eutrophication phenomenon.
Ionizing radiation	kBq Co-60	kBq U235 eq	Ionizing radiation is caused by an emission of radionuclides generated by human activities such

			as mining, waste disposal or burning coal. The exposure to ionizing radiation can damage DNA-molecules leading to cancer. The reference substances are radioactive elements Cobalt 60 and Uranium 235 and kBq is a unity that quantifies the activity of a quantity of radioactive matter.
Ozone depletion	kg CFC-11	kg CFC-11	Stratospheric ozone depletion (also referred as hole in the ozone layer) is caused by an emission of chlorofluorocarbure gases (CFC); it leads to an increase of UV at the ground which infringe ecosystems and human lives. The reference substance is a chlorofluorocarbure gas: CFC-11
Photochemical ozone formation	kg NOx	kg NMVOC	Ozone is formed in the atmosphere by a photochemical reaction of NOx and Non-Methane Volatile compounds. The ozone formation contributes to air pollution and depends on meteorological conditions (ozone pic during summer). Ozone formation infringes both human lives (pulmonary and respiratory diseases increased) and ecosystems (growth and seed production reduced). The reference substances are either nitrogen oxide (NOx) or Non-Methane Volatile Organic Compounds (NMVOC).
Fossil resource scarcity / Energy resource	kg oil	MJ	Fossil resource scarcity relies on the actual fossil resource and a predicted fossil resource extraction. The fossil/ energy resource is either expressed in function of oil, a fossil resource or in energy equivalent.
Mineral resource scarcity	kg Cu	kg Sb	Mineral resource scarcity relies on the actual mineral resource and a predicted mineral resource extraction. The reference substances are metallic element: copper (Cu) and antimony (Sb)
Fine particulate matter formation	kg PM2,5	kg PM2,5	Fine particulate matter formation is caused by an emission volatile organic and inorganic compounds. The fine particulate matter formation contributes to air pollution and have negative impacts on human health (from respiratory issues to death). The reference substance is particulate matter with a diameter smaller than 2,5 micro meters.
Water use	m3 water consumed	m3 water consumed	Water use is based on water consumption: water that is evaporated, incorporated into product, transferred to other watershed or disposed into sea. The unit is a volume of water.

iv. Interpretation of the results

The results of the LCI and LCIA are discussed and presented in the interpretation results phase. The LCIA results can be normalized and weighted in order to ease the result interpretation. Normalization consists in calculating the magnitude of a category impact results in function of a relative information. The normalization can be either internal or external. Internal normalization can only be applied to comparative studies: one of the scenarios of the study is selected as a reference and the other are expressed as function of the reference. External normalization relies on an external reference; it can be applied in all LCA studies. The external normalization is the most common used type of normalization, it usually expresses results regarding to the consumption of a human or the world for one year. Weighting consists in converting the LCIA results into a single environmental score. While weighting, the LCIA results are first normalized and then the contribution of each impact category gives the single score (Pizzol, 2016).

The analysis of uncertainties is also strongly recommended by the ISO 14040 and 14044 when realizing LCA. Indeed, uncertainties are embedded in the calculation of LCA results, the LCA practitioner choices and the data used in LCA. It is important to treat uncertainties in LCA in order to add credibility and reliability to the LCA results. There are three different steps in uncertainties treatment: characterization, analysis and sensitivity. The characterization step corresponds to the characterization of the initial data, LCA model and choices. The analysis of the uncertainties corresponds to the propagation of these characterized uncertainties over the LCA results. Sensitivity analysis allows to determine which data are more disposed to change considerably the LCA results, it helps focusing on the more critical data for uncertainties analysis (Igos et al., 2019). The present study focuses only on the characterization of quantifiable data uncertainties and the propagation of these uncertainties over the LCA method. The propagation method used is the Monte Carlo simulation method: it is a sampled method which gives LCA results distributions in function of the data uncertainties. To be statistically relevant, it requires a large number of simulations between 1,000 and 10,000 runs (Igos et al., 2019).

There are several LCA softwires, including GaBi, Simapro or OpenLCA. All those softwires relies on the same principle: they gather database and characterization method to ease the LCI and LCIA steps of an LCA. OpenLCA is a free software while GaBi and Simapro are proprietary offering a wider range of data and analysis options. The software used in the present study is GaBi. This choice is strategical: GaBi is often used in the industry (Sphera, 2020).

2. GaBi (Thinkstep, 2012)

In the present study, professional GaBi software is referred as GaBi. It is a LCA software easing the LCI and LCIA steps of a LCA. It offers a wide number of life cycle inventories for materials or processes, characterization, normalization and weighting methods.

The functional elements in GaBi are called: flows, processes, plans and balances.

To illustrate properly the GaBi tools, the example of the production of a bottle in plastic is given below.

i. Flows

The flows represent input and output data: they model any substance, energy, matter, co-product, product, emission or waste used during the life cycle of a product. The professional GaBi database includes 29259 flows such as basalt, 1-butanol, electricity or plastic component. There are two fundamental different categories of flows: they can be either elementary or non-elementary flows.

Elementary flows are the flows that come from or go directly to nature; they represent resources or emissions. They are not represented on plans. Among the elementary flows of the plastic bottle production, there are for instance sodium chloride, water or carbon dioxide which are needed for the production of polyethylene granulates (Thinkstep, 2012).

Non-elementary flows, also known as Valuable flows, are flows that are produced by processes and need to be then treated. The valuable flows allow to connect different processes together. They are represented on plans. Among the valuable flows of the plastic bottle, there are for instance polyethylene granulates, the electricity or the plastic bottle itself (Thinkstep, 2012).

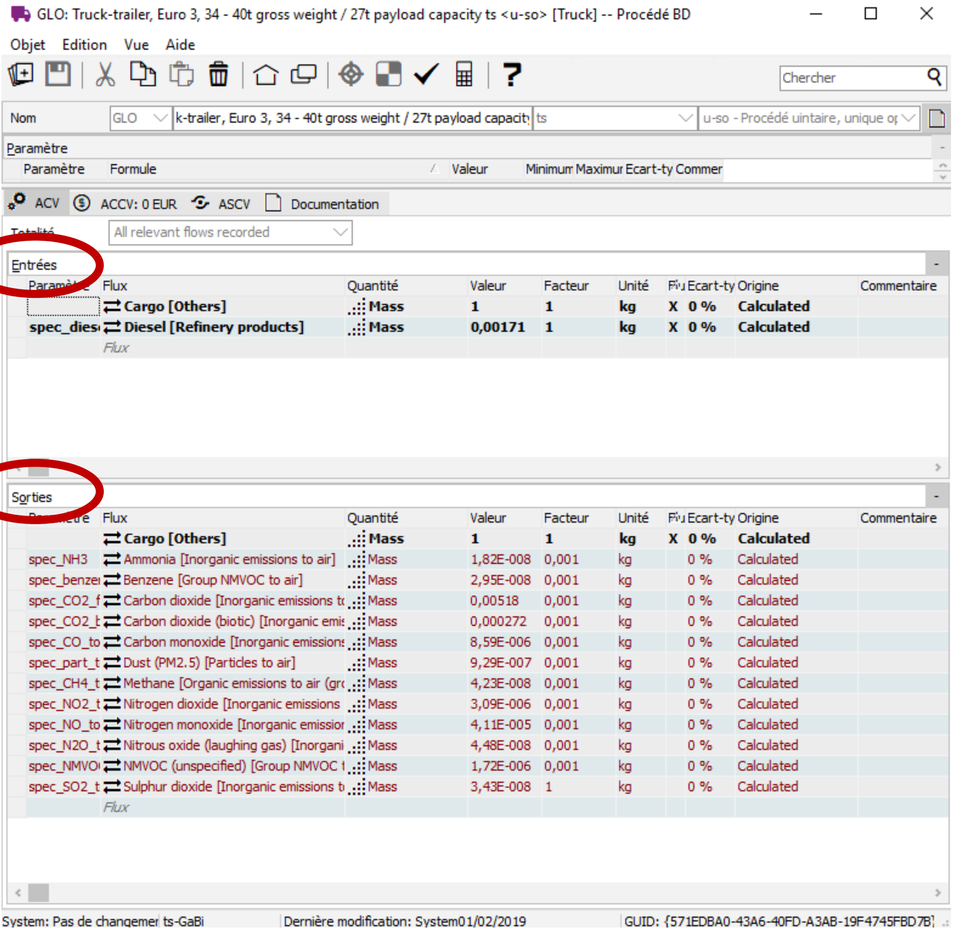
ii. Processes

A process gathers all the input needed and the output generated during the actual process or technical procedure. There are 3,892 ready-made processes in GaBi including production of polyethylene granulates or transport by truck. It is also possible to create new process in GaBi.

Processes can be either labelled as unit process single operation (u-so), unit process black box (u-bb), aggregated (agg), partly aggregated (p-agg) or avoided product system (aps).

Unit process single operation (u-so) also called a gate-to-gate process models only a single step process. Unit process black box models group of processes. Aggregated (agg) and partly aggregated are LCI results and partial LCI results, respectively. Avoided product system are used when a process has several product outputs which is also called an allocation.

Figure 9 is an example of a unit single operation process: the transportation of cargo with a truck. This process models a transport step. The inputs and outputs ("Entrées" and "Sorties", respectively in Fig. 9) are clearly separated. In this example, black flows represent tracked flows: flows that need to be bring from another process or directed to another process (Cargo and Diesel in Fig. 9) while the red flows represent elementary flows (Ammonia, Benzene … in Fig.9)



GLO: Truck-trailer, Euro 3, 34 - 40t gross weight / 27t payload capacity ts <u-so> [Truck] -- Procédé BD

Nom: GLO | k-trailer, Euro 3, 34 - 40t gross weight / 27t payload capacity | ts | u-so - Procédé uintaire, unique op

Paramètre

Paramètre	Formule	Valeur	Minimum	Maximur	Ecart-ty	Commer

Totalité: All relevant flows recorded

Entrées

Paramètre	Flux	Quantité	Valeur	Facteur	Unité	Flu	Ecart-ty	Origine	Commentaire
	Cargo [Others]	**Mass**	**1**	**1**	**kg**	**X**	**0 %**	**Calculated**	
spec_dies	**Diesel [Refinery products]**	**Mass**	**0,00171**	**1**	**kg**	**X**	**0 %**	**Calculated**	
	Flux								

Sorties

Paramètre	Flux	Quantité	Valeur	Facteur	Unité	Flu	Ecart-ty	Origine	Commentaire
	Cargo [Others]	**Mass**	**1**	**1**	**kg**	**X**	**0 %**	**Calculated**	
spec_NH3	Ammonia [Inorganic emissions to air]	Mass	1,82E-008	0,001	kg		0 %	Calculated	
spec_benze	Benzene [Group NMVOC to air]	Mass	2,95E-008	0,001	kg		0 %	Calculated	
spec_CO2_f	Carbon dioxide [Inorganic emissions t	Mass	0,00518	0,001	kg		0 %	Calculated	
spec_CO2_t	Carbon dioxide (biotic) [Inorganic emis	Mass	0,000272	0,001	kg		0 %	Calculated	
spec_CO_to	Carbon monoxide [Inorganic emissions	Mass	8,59E-006	0,001	kg		0 %	Calculated	
spec_part_t	Dust (PM2.5) [Particles to air]	Mass	9,29E-007	0,001	kg		0 %	Calculated	
spec_CH4_t	Methane [Organic emissions to air (gr	Mass	4,23E-008	0,001	kg		0 %	Calculated	
spec_NO2_t	Nitrogen dioxide [Inorganic emissions	Mass	3,09E-006	0,001	kg		0 %	Calculated	
spec_NO_to	Nitrogen monoxide [Inorganic emissior	Mass	4,11E-005	0,001	kg		0 %	Calculated	
spec_N2O_t	Nitrous oxide (laughing gas) [Inorgani	Mass	4,48E-008	0,001	kg		0 %	Calculated	
spec_NMVO	NMVOC (unspecified) [Group NMVOC t	Mass	1,72E-006	0,001	kg		0 %	Calculated	
spec_SO2_t	Sulphur dioxide [Inorganic emissions t	Mass	3,43E-008	1	kg		0 %	Calculated	
	Flux								

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Figure 9 - Example of process: Truck-trailer, Euro 3, 34-40t gross weight/27t payload capacity

Table 2 explains the color coding of flows in Gabi processes. When analyzing a process in detail, it is easy to differentiate the different types of flows due to their colors codings. Elementary flows are either green or red: green if they are considered as an environmental credit and red if an environmental burden. The environmental credits are mainly used when modeling valorization processes such as materials recycling. In the other type of processes such as production, transport or use, the great majority of elementary flows are defined as environmental burden. Usually, valuable flows are in black and bold: they have to be created by a process and bring to another one (Thinkstep, 2012).

Table 2 - Color coding of flows in Gabi processes (Thinkstep, 2012)

	Description	
Bold	Tracked flows: flows that stay in the created technosphere and have to be either brought to the process or treated after	
Black	Valuable flows	
Green	Negative flow value	
	Elementary flows	Non-elementary flows
	Environmental credit	Generation of waste product
Red	Positive flow value	
	Elementary flows	Non-elementary flows
	Environmental burden	Consumed product

iii. Plans

Different processes are combined as a plan which models the entire or a part of a life cycle of a product.

Figure 10 shows the production of a plastic bottle plan. This plan gathers the extraction of the primary material of the bottle (Polyethylene HDPE granulate), the transportation of this matter to the manufacturing place, the shaping of the primary material, the production of the bottle.

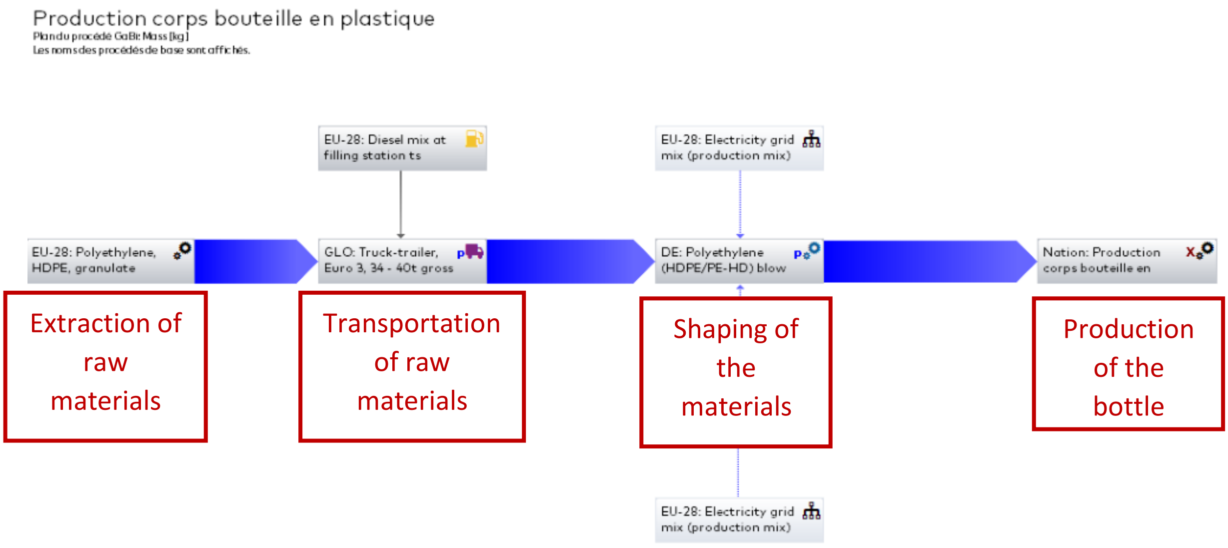
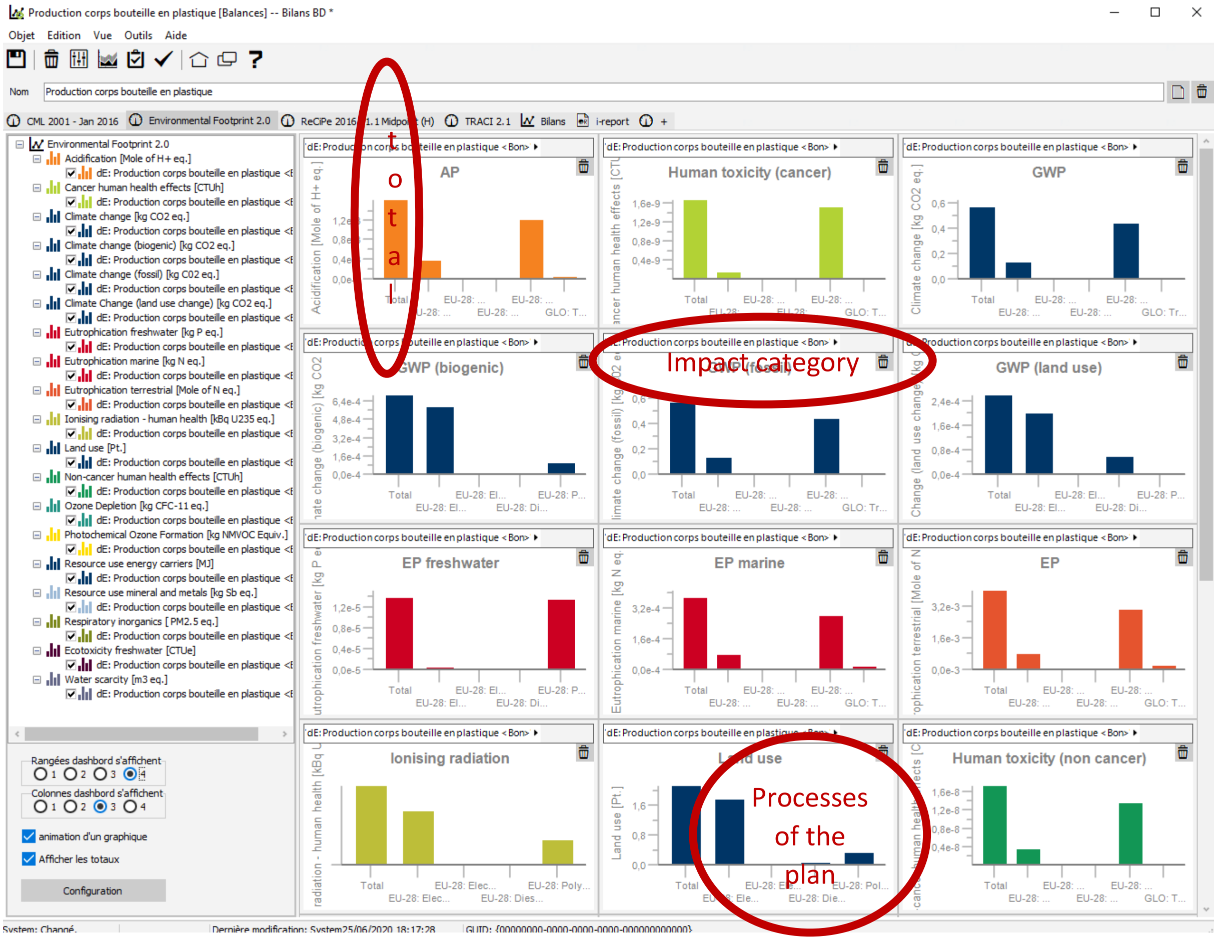


Figure 10 - Example of plan: Production of a plastic bottle

iv. Balances

The balances show the LCI of a product, which is modelled in a plan and evaluate the potential environmental impact on impact categories. The evaluation of those impacts can be done with the desired impact category method: several of them are available on GaBi, including the previously mentioned – ReCiPe and Environmental Footprint.

Figure 11 gives the balance obtained for the plastic bottle production with the Environmental Footprint 2.0 method. Different impact categories are visible, including the Acidification Potential, the different types of Global Warming Potential, the Eutrophication Potential for both fresh and marine waters or the Ionizing radiation. The exact value for each impact categories is given when clicking on the first bar called “Total”. The others bars represent sub processes of the plan.



Production corps bouteille en plastique [Balances] -- Bilans BD *

Nom: Production corps bouteille en plastique

Rangées dashbord s'affichent ○ 1 ○ 2 ○ 3 ● 4

Colonnes dashbord s'affichent ○ 1 ○ 2 ● 3 ○ 4

☑ animation d'un graphique

☑ Afficher les totaux

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Figure 11 - Balance of the plastic bottle production with the Environmental Footprint 2.0 method

III. RESEARCH PART

This thesis focuses on assessing environmental impacts to materials in order to develop an Eco-Design approach at Expleo. The intent is to compare materials and when designing a product be able to choose between two materials according to this grade no matter the final use of the product. To do so, the environmental impact of material production of materials is assessed and the environmental impacts obtained are then translated into grades. The goal of grading is to make the comparison as easy as possible.

This research work steers the materials choices towards reduced environmental impacts by answering the following questions:

i. How to compare materials' environmental impacts during the design process? Step-by-step process for material comparison by using GaBi software and the ReCiPe and Environmental footprint methods.
ii. How to translate the results from the comparison into an easy-accessible format for designers? Prospects and contradiction related to use of impact grade in material selection.

1. Methods

1. Environmental assessment

Goal and scope definition

Goal

The goal of this LCA study is to determine the environmental impact of materials before being used in any final product. The production of materials, including extraction of raw materials and the use of valorized materials, is considered in the present study.

Scope

- Materials under study

Four different materials are chosen for the assessment: two types of aluminium and two types of composites. The materials chosen are the materials used the most by the Calcul division of Expleo. They are all used for aeronautical applications and they can all be used for the structural part of a plane. As mentioned already, weight is a dominant characteristic in aerospace design. Consequently, weight is already taken into account in the design process regardless to the environmental assessment. The other environmental parameters, instead, have not been included in the design process.

The materials chosen are the following:

- Alloy of aluminum:
  1. 2024
  2. 7175
- Composite:
  1. Resin: HexPly® M21 and Fibers: IM7-12K
  2. Resin: CYCOM® 977-20 RTM with PRIFORM Technology and Fibers: 6K-HTA-5HS

- Functional unit

The functional unit is the function given to the studied product in the LCA. The material use is defined only at a very general level: it will be used in plane. Consequently, the only interesting unit is weight. The functional unit is thus the following: "*Manufacturing of 1kg of material*"

- System boundary

At the point of choosing the material, the final structure of the intended component is not available nor is the manufacturing process known. Transportation is independent from the material choice. In aeronautics, the use phase environmental impacts depend strongly on the weight of the parts of the plane. However, weight is included in the technical criteria for choosing materials by the same criteria as for the environmental considerations: the lighter the less fuel consumption and CO2 emissions. Hence, the environmental assessment of the materials relies only on the production of materials from raw or revalorized materials. Only the extraction of raw materials, the valorization of already used materials and the manufacturing of the materials (Fig. 12) are considered.

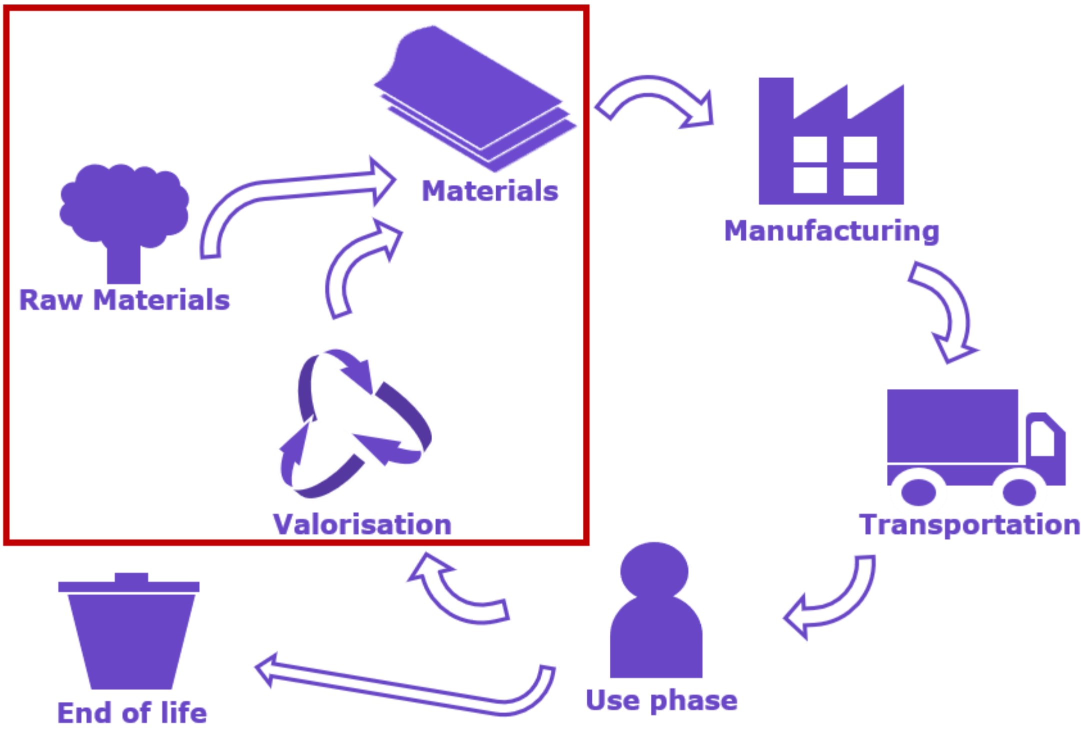

Figure 12 – System boundary

For each material, the final process created is "production of 1 kg material". This final process relies on two sub-processes: "production of 1 kg material from raw materials" and "production of 1 kg material from secondary materials". A recyclability factor R is deduced from literature and give the ratio of each sub-processes leading to the final process.

- LCIA methods and types of impact

Both ReCiPe and Environmental Footprint LCIA methods are used in the present work.

Since the materials are different and their final use is not determined, no impact category can be remoted. The impact categories have been chosen in order to cover all the environmental scope. The impact categories under study are the following:

- Acidification.
- Human toxicity, cancer effect.
- Climate change (incl biogenic carbon).
- Freshwater eutrophication.
- Marine eutrophication.
- Terrestrial eutrophication.
- Ionizing radiation.
- Land use.
- Human toxicity, non-cancer effects.
- Ozone depletion.
- Photochemical ozone formation.
- Resource depletion, fossils.
- Resource depletion, metals & mineral.
- Particulate matter.
- Ecotoxicity freshwater.
- Resource depletion water.

Life Cycle Inventory (LCI)

For each material, the LCI is established following these steps:

i. Study of the material manufacturing: raw materials and different steps leading to the final material
ii. Modelling of the different manufacturing steps into processes on GaBi:
    - Use of already existing GaBi processes in priority if possible
    - Creation of processes on GaBi if no Gabi processes available
iii. Integration of recyclability of materials If possible

If a manufacturing step has to be created (i.e. in the cases for which GaBi does not have a process available), the LCI template (table 3) has to be fulfilled. The information for the manufacturing is sought from literature by using the name of the missing steps as search words. The sources are clearly stated in order to check further the liability and precision of data.

Table 3 - LCI template

	Sub-steps or flow categories	Flows	Unity	Quantity	Sources
Manufacturing step	INPUTS				
	OUTPUTS				

Life Cycle Impact assessment

The LCIA is performed using the LCA software GaBi.

Interpretation of the results

The gross impact results of the selected impact categories are not analyzed in details. They are translated into environmental grades using a normalization and weighting: these two steps belong to the Grading System section.

2. Grading system

The grading system developed is derived from a normalization of the impact categories followed by a weighting method as part of this thesis work. The grade itself is formed to express multiple impacts as one score. This score represents the sum of the environmental impacts of each impact category for the production of 1kg of materials and thus it is a scalar/kg of materials produced. Consequently, the lower the grade, the less the environmental impact of the material is.

The grade is obtained according to the following equation:

Equation 1 - Grade

$$GRADE(material) = \sum_{i \text{ the Impact categories}} Wf_i . Nf_i . IC_i(material)$$
$$= \sum_{i \text{ the Impact categories}} grade_i(material)$$

Where:

- i corresponds to a given impact category (table 4).
- Wf_i is the weighting factor associated to the i impact category (table 5).
- Nf_i is the normalization factor associated to the I impact category (table 4).
- $IC_i(material)$ is the results on the i impact category of the material (appendix B).
- $grade_i(material)$ is the subgrade associated to the i impact category of the material.

The normalization and weighting steps are two questioned steps in LCA, the normalization and weighting methods chosen are commonly accepted by the LCA practitioners (i.e. already implemented in the GaBi software). The normalization depends on the characterization method (i.e. normalization method has to be given by the same comity that develops a characterization method). The normalization factors for the ReCiPe method are not available, hence the grade classification using the ReCiPe method is currently impossible. The weighting method used is determined by Castellani in 2016. (Castellani et al., 2016)

The normalization and weight factors used are given in the tables 4 and 5.

Table 4 - Normalization factors (Sala et al, 2017)

Impact categories (IC)	Normalization factors (Nf)		
	ReCiPe	Environmental Footprint	
		Value	Unity
Acidification	**NOT AVAILABLE**	55,5	Mole of H+
Human toxicity, cancer effects		3,85E-05	CTUh
Climate change, incl biogenic carbon		8400	kg of CO2
Eutrophication freshwater		0,734	kg P
Eutrophication marine		28,3	kg N
Eutrophication terrestrial		177	Mole of N

Ionizing radiation		422	kBq U235
Land use		1400000	Pt
Human toxicity, non-cancer effects		4,75E-04	CTUh
Ozone depletion		2,34E-2	kg CFC 11
Photochemical ozone formation		40,6	kg NMVOC
Resource depletion fossils		65300	MJ
Resource depletion, mineral		6,36E-2	kg SB
Particulate matter		7,18E-4	PM2,5
Ecotoxicity freshwater		11800	CTUe
Resource water depletion		11500	m^3

Table 5 - Weight factors (Castellani et al., 2016)

IMPACT CATEGORIES (IC)	Weight factors (Wf)
Acidification	1,18
Human toxicity, cancer effects	1,12
Climate change, incl biogenic carbon	1,16
Eutrophication freshwater	1,01
Eutrophication marine	1,13
Eutrophication terrestrial	1,14
Ionizing radiation	1
Land use	1,15
Human toxicity, non-cancer effects	1,01
Ozone depletion	1,05
Photochemical ozone formation	1,28
Resource depletion fossils	0,65
Resource depletion, mineral	0,65
Particulate matter	1,21
Ecotoxicity freshwater	1,1
Resource depletion water	6,38

3. Evaluation of uncertainties

The evaluation of uncertainties relies on the created processes. Some flow values of the created processes are uncertain: literature gives a range of value for a same flow or the flow value is deduced from other processes. The Gabi processes, the normalization and weighting steps are considered as more precise than the created processes.

First, for each plan created, an analysis of the data quality is given. This analysis is based on the Data Quality Indicators of GaBi which is a table that give the process integrity and the origin of data in processes. The process integrity consists in verifying that every valuable substance (i.e. substance which is not natural resource nor an emission) comes from a process and is used in another one.

Then, for each process created, the liability of each source of a process is questioned and qualified. Parameters for the less certain data are then created and the standard deviation for each parameter is determined. The following table 6 gives the template that has to be filled for each parameter.

Table 6 - Parameters

Materials	Process	Parameters	Standard deviation %

Finally, Monte Carlo simulations are performed for each material. 1,000 simulations are run for each material. Based on these Monte Carlo simulations, the standard deviations of parameter are translated into standard deviations for each impact category result.

The standard deviation of each impact category result determines the statistical uncertainty on the impact category result. Indeed, the statistical uncertainty can be expressed as:

Equation 2 – Statically uncertainty

$$u_{IC_i}(material) = \frac{\sigma_{IC_i}(material)}{\sqrt{n}}$$

Where:

- IC_i stands for the impact category i
- σ_{IC_i} the standard deviation obtained for this impact category i during Monte Carlo simulations
- n le number of simulations runs

The weighting and normalization factors are supposed to be more accurate than the impact categories results. Thus, their relative uncertainty is supposed to be negligible compared to the impact category results one. Based on these uncertainty assumptions, the uncertainty related to the grade can be determined as follow:

Equation 3 – Relative uncertainty of $grade_i(material)$

$$\frac{u_{grade_i}(material)}{grade_i(material)} = \sqrt{\frac{(u_{Wf_i})^2}{{Wf_i}^2} + \frac{(u_{Nf_i})^2}{{Nf_i}^2} + \frac{(u_{IC_i}(material))^2}{IC_i(material)^2}} \simeq \sqrt{\frac{(u_{IC_i}(material))^2}{IC_i(material)^2}}$$

Where:

- Wf_i is the weighting factor associated to the i impact category (table 5).
- Nf_i is the normalization factor associated to the I impact category (table 4).
- $grade_i(material)$ is the subgrade associated to the i impact category of the material.

Equation 4 – Uncertainty of $GRADE(material)$

$$u_{GRADE}(material) = \sqrt{\sum_{i\,IC} (u_{grade_i}(material))^2}$$

2. Results

1. Environmental assessment

Scope

The scope of materials is reduced due to a lack of information and precision on composite process of fabrication and on GaBi database, it is not possible to distinguish the two different composites. Few data are available on the industrial processes of carbon composite. Hence, there is not two specific composites under study but an average one.

LCI

Alloy of aluminium

i. Data collection for manufacturing steps of aluminium alloys

Aluminium is a metal that cannot be extracted from the nature. Aluminium must be produced first and then impurities are added to created aluminium alloys. Aluminium is produced from alumina Al2O3. The production of aluminium alloys relies on the following steps (*L ' aluminium*, 2016):

1. Bauxite extraction
2. Extraction of alumina from bauxite
3. Electrolyse of alumina into aluminium
4. Solid solution of aluminium and the different precipitate
5. Other treatment (thermal, mechanical)

Aluminium alloys are classified according to the type and amount of impurities added (*L ' aluminium*, 2016). The chemical composition of each alloy is given in table 7. The compositions are obtained from the Euralliage website (Euralliage, 2024, 2020) (Euralliage, 7175, 2020).

Table 7 - Chemical composition of the alloys under study

	Chemical formula	Chemical composition									
		Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Other	Al
2024 (Euralliage, 2024, 2020)	$AlCu_4Mg_1$	0,5	0,5	3,8-4,9	0,3-0,9	1,2-1,8	0,1	0,25	0,15	0,15	90,75-93,05
7175 (Euralliage, 7175, 2020)	$AlZn_{5,5}MgCu$	0,15	0,20	1,2-2,2	0,10	2,1-2,9	0,18-0,28	5,1-6,1	0,1	0,15	87,82-90,72

ii. Modelling of the Aluminium alloy manufacturing in GaBi

The three first steps of aluminium alloys manufacturing are already existing as Gabi processes (i.e. Bauxite extraction, extraction of alumina and electrolysis of alumina into aluminium). The fourth step is modelled. The other treatments of aluminium alloy depend on the final use of the alloy, while the fifth step is remoted from this study.

The LCI for the fourth modelled step are given in table 8 for Aluminium alloy 2024 and table 9 for Aluminium alloy 7175, respectively.

Table 8 – LCI Aluminium 2024 ingot

	Sub-steps or flow categories	Flows	Unity	Quantity	Sources
Primary Aluminium 2024 ingot	INPUTS				
	Chemicals compound	Aluminium	kg	0,919	Deduced from the chemical composition of 2024 (table 7)
		Cast iron	kg	0,005	
		Copper	kg	0,0435	
		Ferro-chrome (60% Cr)	kg	0,0017	
		Ferro-manganese (80 to 85% Mn)	kg	0,0073	
		Magnesium	kg	0,015	
		Silicon	kg	0,0055	
		Zinc redistilled zinc	kg	0,0025	
		Titanium	kg	0,0015	
	Energy	Electricity	MJ	34,1	Deduced from Gabi Aluminium ingot mix process
	OUTPUTS				
	Product	Primary Al 2024 ingot	kg	1	
	Waste	Ferro-waste	MJ	0,0019	

Table 9 – LCI Aluminium 7175 ingot

	Sub-steps or flow categories	Flows	Unity	Quantity	Sources
Primary Aluminium 7175 ingot	INPUTS				
	Chemicals compound	Aluminium	kg	0,887	Deduced from the chemical composition of 7175 (table 7)
		Cast iron	kg	0,002	
		Copper	kg	0,0017	
		Ferro-chrome (60% Cr)	kg	0,0038	
		Ferro-manganese (80 to 85% Mn)	kg	0,00121	
		Magnesium	kg	0,0025	
		Silicon	kg	0,00152	
		Zinc redistilled zinc	kg	0,056	
		Titanium	kg	0,001	
	Energy	Electricity	MJ	34,1	Deduced from Gabi Aluminium

					ingot mix process
	OUTPUTS				
	Product	Primary Al 7175 ingot	kg	1	
	Waste	Ferro-waste	MJ	0,00173	

iii. Integration of recyclability of materials

Aluminium is assumed to be "infinitely" recyclable, which means that it can be recycled indefinitely (Aluminium, 2020). This fact has to be taken into account while modeling the manufacturing of aluminium alloys.

Two additional processes have been created: these processes model an aluminium alloy manufacturing using recycled aluminium. The aluminium flow is removed and an additional amount of energy is added. The additional amount of energy represents the amount of energy needed to recycle 1kg of aluminium. The LCI of the ingots aluminium 2024 and 7175 from recycled aluminium are given in table 10 and table 11, respectively.

Table 10 - LCI Aluminium 2024 from recycled aluminum

	Sub-steps or flow categories	Flows	Unity	Quantity	Sources
Secondary Aluminium 2024 ingot	INPUTS				
	Chemicals compound	Cast iron	kg	0,005	Deduced from the chemical composition of 2024 (table 4)
		Copper	kg	0,0435	
		Ferro-chrome (60% Cr)	kg	0,0017	
		Ferro-manganese (80 to 85% Mn)	kg	0,0073	
		Magnesium	kg	0,015	
		Silicon	kg	0,0055	
		Zinc redistilled zinc	kg	0,0025	
		Titanium	kg	0,0015	
	Energy	Electricity for ingot	MJ	34,1	Deduced from Gabi Aluminium ingot mix process
		Electricity for recycling aluminium	MJ	7,51	
	OUTPUTS				
	Product	Primary Al 2024 ingot	kg	1	
	Waste	Ferro-waste	MJ	0,0019	

Table 11 - LCI Aluminium 7175 from recycled aluminium

	Sub-steps or flow categories	Flows	Unity	Quantity	Sources
	INPUTS				
		Cast iron	kg	0,002	

Secondary Aluminium 7175 ingot	Chemicals compound	Copper	kg	0,0017	Deduced from the chemical composition of 2024 (table 4)
		Ferro-chrome (60% Cr)	kg	0,0038	
		Ferro-manganese (80 to 85% Mn)	kg	0,00121	
		Magnesium	kg	0,0025	
		Silicon	kg	0,00152	
		Zinc redistilled zinc	kg	0,056	
		Titanium	kg	0,001	
	Energy	Electricity for ingot	MJ	34,1	Deduced from Gabi Aluminium ingot mix process
		Electricity for recycling aluminium		7,51	
	OUTPUTS				
	Product	Secondary Al 7175 ingot	kg	1	
	Waste	Ferro-waste	MJ	0,00173	

To obtain the final ingot process for both aluminium 2024 and 7175, a recyclability rate R is established. R represents the percentage of aluminium that is currently recycled in a chosen geographic area. For the case of this study, the geographic area is France and thus R=0,47. (Aluminium, 2020)

Two final ingot processes are created in order to take into account the valorization of aluminium matter. These two processes are sufficiently similar and the final result is given in table 12.

Table 12 - Final LCI aluminium alloys

	Sub-steps or flow categories	Flows	Unity	Quantity	Sources
Aluminium 2024/7175 ingot	INPUTS				
		Primary Al 2024/7175 ingot	kg	1-R	
		Secondary Al 2024/7175 ingot	kg	R	
	OUTPUTS				
		Aluminium 2024/7175 ingot	kg	1	

Carbon fiber/ epoxy composites

Two composites (HexPly® M21 and Fibers: IM7-12K vs CYCOM® 977-20 RTM with PRIFORM Technology and Fibers: 6K-HTA-5HS) were compared. However, due to a lack of data, the distinction between the two composite is impossible. Consequently, the LCA process is done for only one resin which represents the both composite.

i. Data collection for manufacturing of carbon fiber/epoxy composite

The composite considered is a made with an epoxy matrix and carbon fibers reinforcement.

The manufacturing of the matrix relies on two steps (Bardonnet & Bardonnet, 2016):

1. Preparation of the resin molecule
2. Reticulation of the resin molecule into a cross-linked resin

95% of epoxy resin are produced from bisphenol A precursor (Bardonnet & Bardonnet, 2016). Most of the time, the epoxy resin is activated into a cross-linked resin using a hardener (Bardonnet & Bardonnet, 2016). The hardener considered in the study is a hexamethylene diamine (HDMA): amine hardeners are common for epoxy composites and HDMA was the only hardener available in the Gabi database.

The carbon fibers used for reinforcement application are produced from either mesophase pitch or polyacrylonitrile (PAN) precursors. The most used carbon fiber precursor is the PAN precursor. PAN precursors are produced by polymerization and spinning of acrylic fibers leading to PAN fibers. The manufacturing of the carbon fibers relies on five steps (Luyckx, 1999):

1. Oxidization of PAN fibers
2. Carbonization
3. Graphitization (optional step)
4. Surface treatment
5. Ensimage

The matrix and the reinforcement are then mixed in order to create a composite. There are several ways to mix the matrix and the resin: in aeronautics, the carbon composites are mainly available as pre-impregnated. (Aliaga,D. & al, 2014)

ii. Modelling of the different manufacturing steps into processes on GaBi

The manufacturing of epoxy resin and the HDMA hardener processes are already implemented into the Gabi database. The production of carbon fibers and the assembly of the composite processes have to be created. Table 13 and 14 gives the LCI of the carbon fibers production and the composite assembly, respectively.

Table 13 - LCI Carbon fibers production

	Sub-steps or flow categories	Flows	Unity	Quantity	Sources
Carbon fiber production	INPUTS				
	PAN fibers production	Polyacrylonitrile fibers	kg	1,61	Deduced from chemical equation given in appendix **A**
	Oxidization	Oxygen gaseous	kg	0,485	
	Carbonization	Nitrogen liquid	kg	0,212	
	Energy	Electricity	MJ	149,4	(Meng et al, 2018)
		Thermal energy from natural gas	MJ	177,8	
		Steam	kg	31,4	
	OUTPUTS				
	Product	Carbon fibers	kg	1	

	Wastes	Ammonia	kg	0,129	Deduced from chemical equation
		Hydrogen	kg	0,06	
		Hydrogen cyanide	kg	0,205	
		Nitrogen monoxide	kg	0,909	

Table 14 - LCI composite assembly

	Sub-steps or flow categories		Flows	Unity	Quantity	Sources
Composite assembly - pre preg	INPUTS					
	Reinforcement		Carbon fibers	kg	0,660	Ratio Reinforcement/Matrix extracted from (Hexcel Composites, 2003)
	Matrix	Resin	Epoxy resin	kg	0,291	Ratio Resin/Hardener calculated according to Epoxycuring
		Hardener	Hexamethylene diamine (HDMA)	kg	0,049	
	Energy		Electricity	MJ	18-40	(Bachmann et al, 2017)
	OUTPUTS					
	Product		Composite carbon/epoxy	kg	1	

iii. Integration of recyclability of materials

There is currently no industrial way to recycle carbon composites with no loose of properties (i.e. recycled carbon fibers cannot be used as virgin carbon fibers). No recyclability process has been modelled.

All the GaBi plan created for each material are given in appendix **B**.

Interpretation of the results

The tables 15 and 16 presents the environmental impact of materials for each impact category using the ReCiPe and Environmental footprint methods, respectively.

Table 15 - Environmental impacts of the materials using the ReCiPe method

Impact categories	**Unit**	**2024**	**7175**	**Carbon composite**
Acidification potential	kg SO2	1,84E-02	1,60E-02	3,91E-01
Human toxicity (cancer)	kg 1,4 DCB	4,48E-03	3,98E-03	1,37E-02
Climate change	kg CO2	8,01E+00	7,45E+00	3,70E+01

Eutrophication freshwater	kg P	1,48E-05	1,51E-05	6,90E-05
Eutrophication marine	kg N	1,24E-04	1,24E-04	9,17E-03
Eutrophication terrestrial	kg 1,4 DCB	1,58E+01	6,91E+00	1,32E+01
Ionizing radiation	Bq C-60	3,45E-01	3,43E-01	8,07E-01
Land use	Annual crop eq yr	3,79E-01	4,61E-01	1,13E+00
Human toxicity (non-cancer)	kg 1,4 DCB	5,45E-01	3,67E-01	1,29E+00
Ozone depletion potential	kg CFC 11	2,12E-6	1,99E-6	1,85E-5
Photochemical ozone formation	kg NOx	1,18E-02	9,03E-03	9,74E-01
Resource energy	kg oil	2,86E+00	2,75E+01	1,53E+01
Resource use minerals and metals	kg Cu	1,15E-01	6,95E-02	2,83E-02
Particulate matter	PM2,5	9,88E-03	5,34E-03	1,21E-01
Ecotoxicity freshwater	kg 1,4 DCB	-2,95E-04	5,55E-04	3,55E-03
Freshwater consumption	m3	3,15E-02	2,89E-02	1,09E-01

Table 16 - Environmental impacts of the materials using the Environmental footprint method

Impact categories	**Unit**	**2024**	**7175**	**Carbon composite**
Acidification potential	mole of H+	2,68E-02	2,34E-02	7,74E-01
Human toxicity (cancer)	CTUh	1,26E-08	1,04E-08	1,13E-07
Climate change	kg CO2	8,02E+00	7,46E+00	3,71E+01
Eutrophication freshwater	kg P	1,48E-05	1,51E-05	6,90E-05
Eutrophication marine	kg N	4,04E-03	3,17E-03	3,80E-01
Eutrophication terrestrial	mole of N	4,30E-02	3,95E-02	4,15E+00
Ionizing radiation	kBq U235	2,14E+00	2,12E+00	4,49E+00
Land use	Pt	7,06E+01	6,61E+01	2,32E+02
Human toxicity (non-cancer)	CTUh	4,87E-07	3,50E-07	2,84E-06
Ozone depletion potential	kg CFC 11	6,89E-14	6,94E-14	2,72E-13
Photochemical ozone formation	kg NMVOC	1,18E-02	1,07E-02	6,64E-01

Resource energy	MJ	1,24E+02	1,20E+02	6,53E+02
Resource use minerals and metals	kg SB	1,54E-04	2,62E-04	4,98E-06
Particulate matter	PM2,5	3,80E-07	3,15E-07	1,70E-06
Ecotoxicity freshwater	CTUe	-1,13E+00	-1,22E+00	2,05E+00
Water use	m3	1,13E+00	1,04E+00	3,80E+00

Fundamentally, the impact on an impact category from one characterization method to another are not the same, except for the eutrophication freshwater category. These discrepancies come from the fact that each characterization method is not using the same mathematical model nor taking the same number of substances to modelled the impact categories. (ESU services, 2019) Except for land use, ozone depletion and resource use minerals and methods, both ReCiPe and Environmental footprint rank the material similarly for each impact category. When the environmental impacts for a category are ranked for instance 2024 < 7175 < Composite with a method, it is the same with the other method. Since there is no normalization method available for ReCiPe, it is difficult to determine if the discrepancies between impacts results from one method to another represents an issue for the grading system. Indeed, since each normalization method is constructed in a function of a characterization method, the difference could be reduced.

2. Grading system

The normalized results obtained with the Environmental Footprint 2.0 are given in appendix **C**. The normalized results are then multiplied by their respective weighting factors and sum up to lead to the grade (Equation 1).

The obtained environmental grades are given in table 17.

Table 17 - Environmental grades

Materials	Grades (x 10^{-3})/ kg of material produced
Aluminium 2024	13,0
Aluminium 7175	13,3
Carbon composite	116

There is a small yet significant difference between the two aluminium alloys grades. The 2024 aluminium alloy receives a smaller environmental grade and thus has less environmental impact than the 7175 aluminium alloy. This difference can be explained by the higher concentration of heavy metals in the 7175 (around 7%) than the 2024 (around 4%). Indeed, copper and zinc are classified as heavy metals and to some extent, they can be harmful for both human and ecosystems.

There is a significant difference between the aluminium alloys grades and the carbon composite's. This difference is mainly due to the energy consumption of the processes. In fact, producing 1 kg of composite requires 10 times the energy needed to produce 1 kg of alloy.

3. Evaluation of uncertainties

The table of Data Quality Indicators taken from the GaBi tool is given in table 16. First for the process integrity, the great majority of flows for the studied materials are captured in the processes (above 95 % see table 16). The percentages of flows with no indication take into account the final material created. Indeed, each final material is created in a process which is not linked to any other process. The final materials flows are uncaptured flows. Secondly, for the inputs and outputs of processes, 72,1% of data (sum of percentage of measured, calculated, literature and estimated data see table 16) have a stated source origin. An ideal set of data would be with equal percentage for each source origin. It is not the case here. However, the present data repartition is assumed to be sufficiently reliable.

Table 18 - Data Quality Indicators from GaBi tool

	Process's integrity		Processes: Inputs & Outputs				
	All relevant flows captured	No indication	Measured	Calculated	Literature	Estimated	No indication
Aluminium 2024	95,5 %	4,47 %	2,21 %	30,6 %	36,7 %	2,58 %	27,9 %
Aluminium 7175	95,5 %	4,47 %	2,21 %	30,6 %	36,7 %	2,58 %	27,9 %
Carbon composite	95,2 %	4,76 %	2,21 %	30,6 %	36,7 %	2,59 %	27,9 %

The obtained environmental grades and their uncertainties are given in table 17.

An excel sheet with all the intermediate steps for determining the uncertainties is given in appendix **D**.

Table 19 - Environmental grades and uncertainties

Materials	Grades (x 10^{-3})/kg of material produced	Uncertainties (x 10^{-3})/kg of material produced	Relative uncertainties %/kg of material produced
Aluminium 2024	13,0	± 2	± 15
Aluminium 7175	13,3	± 2	± 15
Carbon composite	116	± 11	± 10

The uncertainties on the grade of Aluminium 2024 and 7175 prevent from ranking the environmental performance of these two aluminium alloys. According to the established grading system, the aluminium alloys can be considered as equal environmentally speaking.

The uncertainties on aluminium alloys and carbon composite allow to rank their environmental performances. Indeed, based on the established grading system, the carbon composite grade is 10 times the aluminium alloys ones. The carbon composite appears to be less environmentally friendly than both aluminium alloys.

IV. CONCLUSION

The present study provides environmental grading system for materials in aeronautics for improved selection of the eco-design process. This grading system has for aim to make easier the eco-design process. The study was conducted on four materials: aluminium alloy 2024, aluminium alloy 7175 and two carbon fiber/epoxy resin composite: Resin: HexPly® M21/Fibers: IM7-12K and Resin: CYCOM® 977-20 RTM with PRIFORM Technology/Fibers: 6K-HTA-5HS.

This research work indicates the materials choices towards reduced environmental impacts is driven by the following questions:

i. How to compare materials' environmental impacts during the design process?
ii. How to translate the results from the comparison into an easy-accessible format for designers?
iii. What are the uncertainties related to the assessment process and the grading?

The LCA software GaBi was quite easy to use. First, the plan function of GaBi helps to overview the different steps in the production of materials. Then, the impact assessment results were easily available thanks to the balance function. Finally, GaBi eased the evaluation of uncertainties on LCA results step. However, the study was limited by the GaBi database. Indeed, the composites were considered as one average composite because of first a lack of data on the process composite but also a lack of precision on the GaBi database.

The impact assessment methods, ReCiPe and Environmental footprint, are not based on the same mathematical model and they are not taking into account the same number of substances for each impact category (ESU services, 2019). Hence, they gave similar yet differing results. Since there is no normalization available for ReCiPe, it is difficult to say if the difference of the impact assessment methods would affect the final grades.

The LCA results show a significant difference between the two alloys and the carbon composite grades: the environmental grade of the carbon composite is 10 times higher than the alloys ones. It means that according to this grading system, the production of 1 kg of carbon composite is environmentally worse than the production of 1kg of one of the alloys. This difference is explained by the energy intensive aspect of the carbon fiber production. The results show a slight difference between the aluminium alloys grades: the 7175 aluminium grade is 2% superior to the 2024 aluminum's. Yet, the uncertainties on the grades prevent any conclusion on their relative environmental performances.

The grades have to be considered with the hypothesis made:

a. these grades only take into account few steps of the life cycle,

b. they are relative to a quantity of matter (1kg) and not a use (i.e. to design the same piece it is possible not to use the same quantity of materials, depending on the materials' mechanical properties).

To pursue this, these studies need to be extended to model a product that can be made with either aluminium alloys or carbon composite. Further studies should also use these results and focus on the other life cycle steps of the product, in order to evaluate the environmental impact of each product.

This way, the other life cycle steps is be taken into account and the relevance of focusing only on the materials production step is be verified.

Then, data collection is limiting. The lack of industrial information prevents from distinction of the two composites selected at the beginning of the study. This lack of information probably also prevents to make any comparison between the two aluminium alloys. A deeper and much longer research investigation on data and contacts from industrial materials producers is necessary to overcome this limitation.

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APPENDICES

Appendix A: Carbon fibers chemical reaction

The oxidation reaction of the PAN fibers is supposed to be the following (Kelly, n.d.):

$$\mathbf{(C_3H_3N)_n + {}^{1}\!/_{2}\,nO_2 + \rightarrow (C_3HNO)_n + 2nH}$$

During the carbonization half of the PAN based fibers mass is evaporated into gaseous molecules.

The carbonization reaction of the PAN fibers is supposed to be the following (Kelly, n.d.)

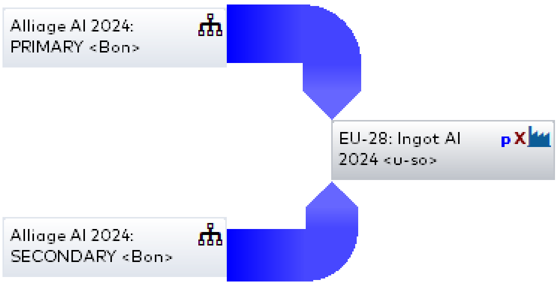
$$\mathbf{4C_3HNO + N_2 \rightarrow 11C + HCN + NH_3 + 4NO}$$

Appendix B: Plan created on GaBi

I. Aluminium alloy 2024

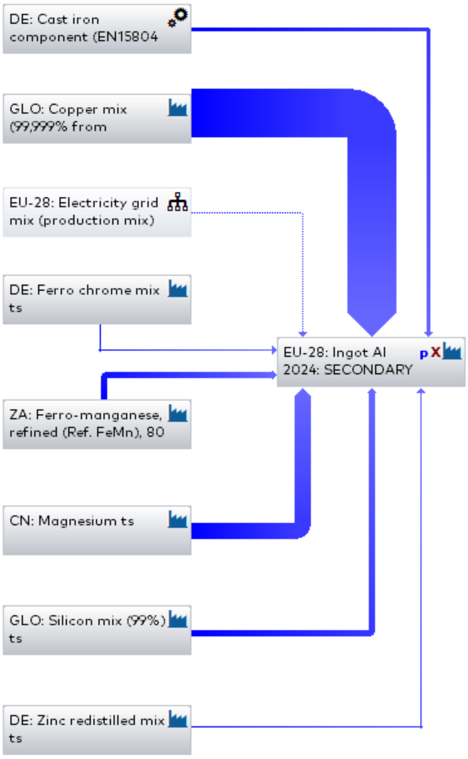
Al 2024

Plan du procédé GaBi: Mass [kg]
Les noms des procédés de base sont affichés.



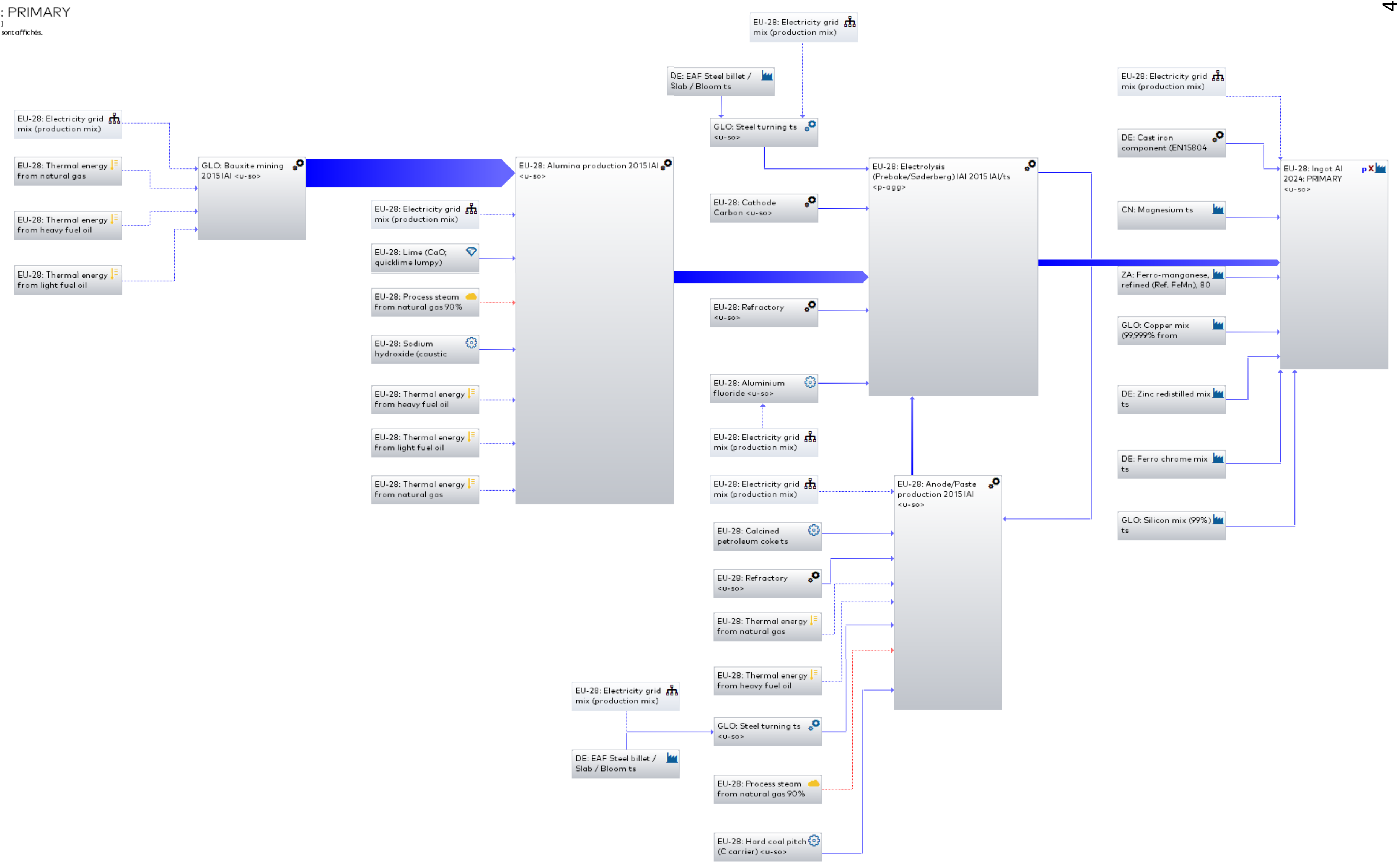
Alliage Al 2024: SECONDARY

Plan du procédé GaBi: Mass [kg]
Les noms des procédés de base sont affichés.



Alliage Al 2024: PRIMARY

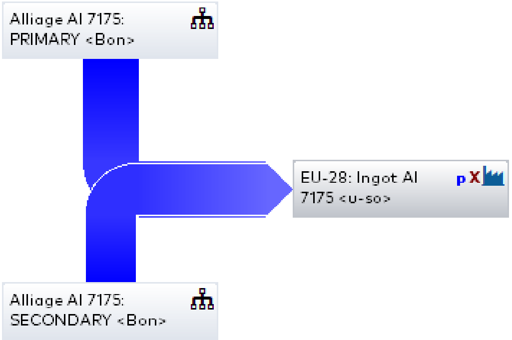
Plan du procédé GaBi: Mass [kg]
Les noms des procédés de base sont affichés.



II. Aluminium alloy 7175

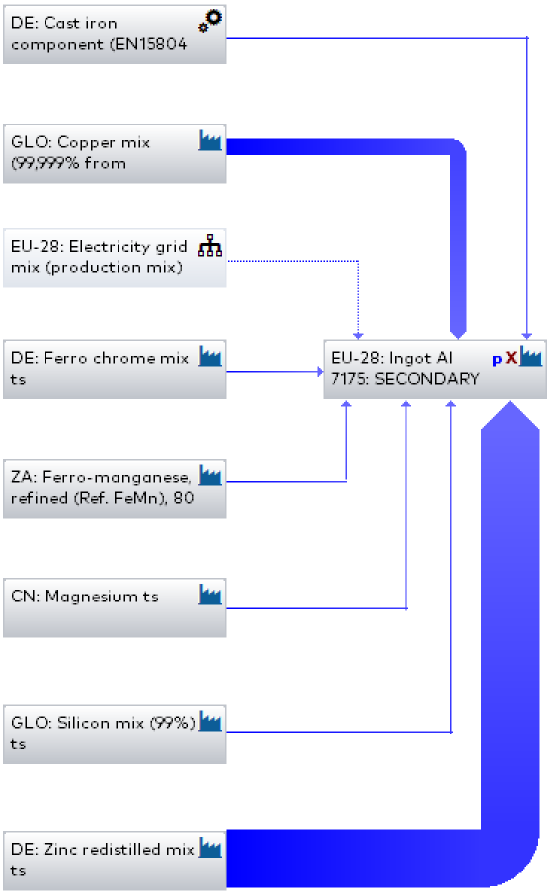
Al 7175

Plan du procédé GaBi: Mass [kg]
Les noms des procédés de base sont affichés.



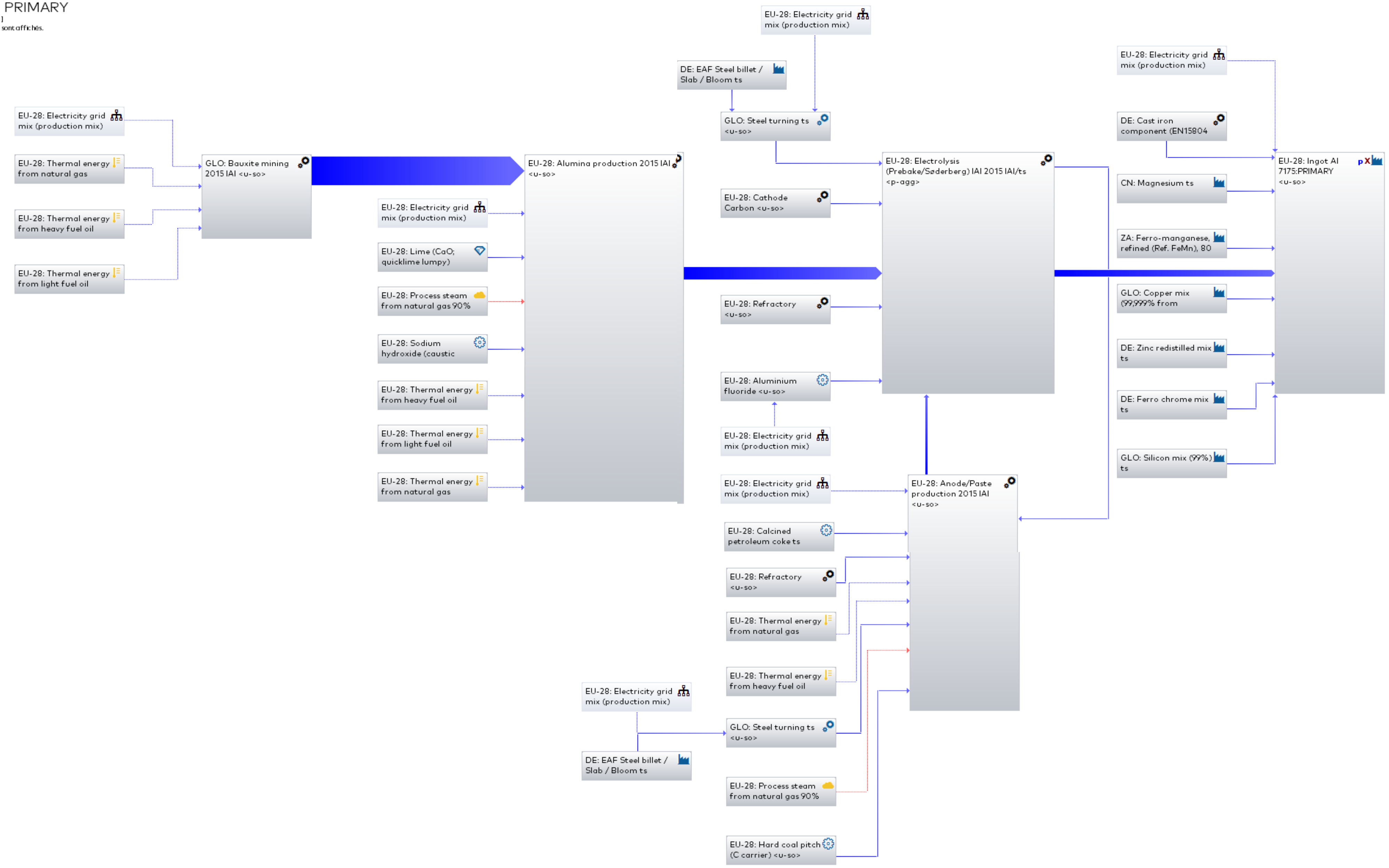
Alliage Al 7175: SECONDARY

Plan du procédé GaBi: Mass [kg]
Les noms des procédés de base sont affichés.



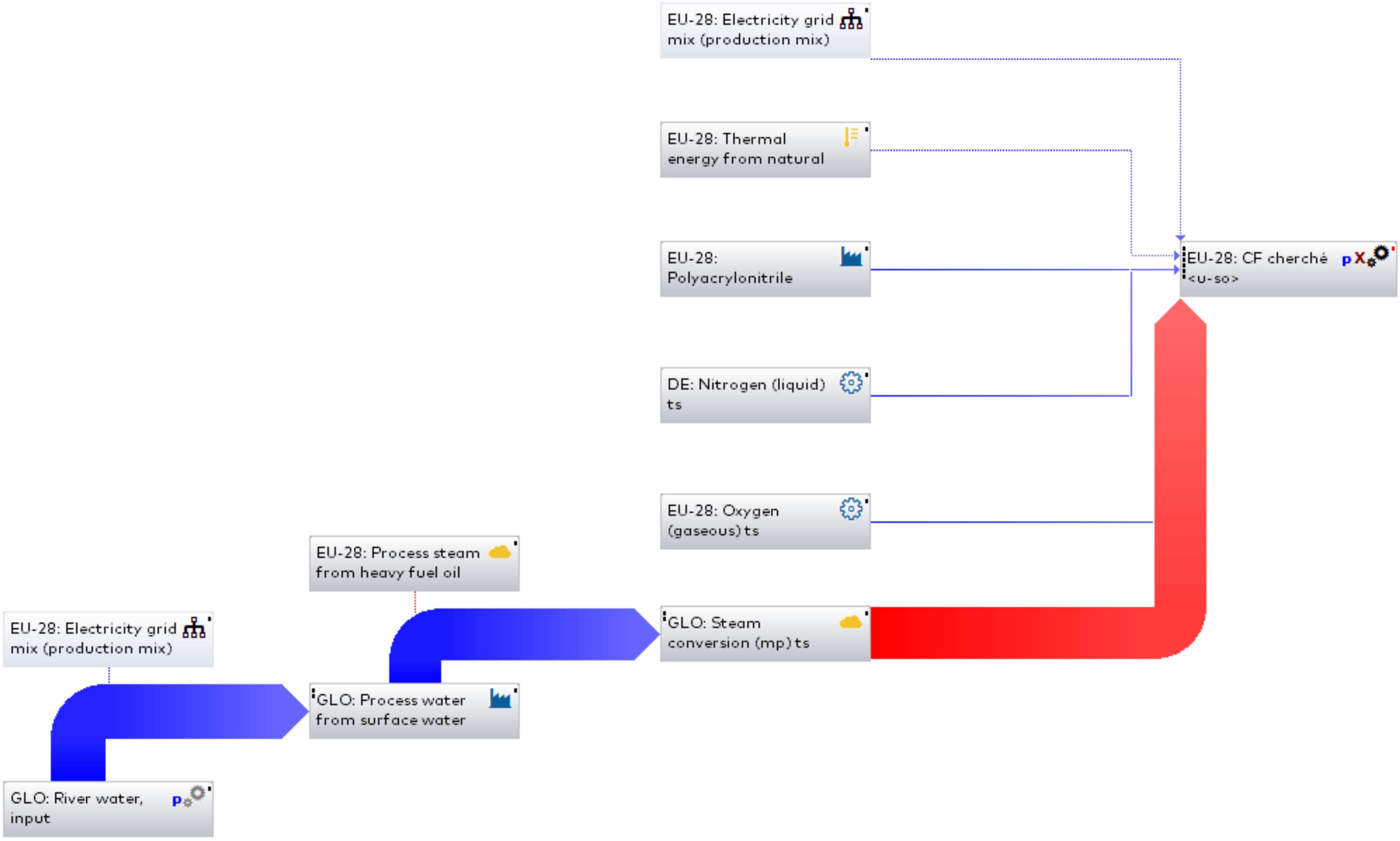
Alliage Al 7175: PRIMARY

Plan du procédé GaBi: Mass [kg]
Les noms des procédés de base sont affichés.



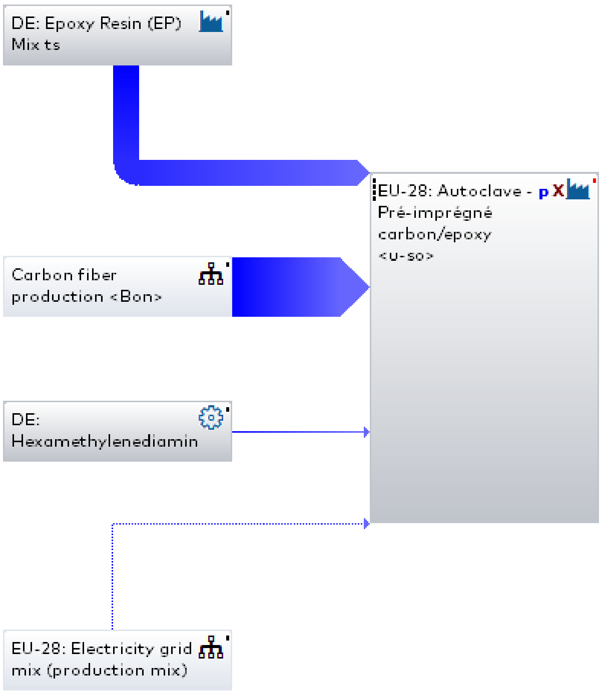
III. Carbon/epoxy composite

Carbon fiber production
Plan du procédé GaBi: Mass [kg]
Les noms des procédés de base sont affichés.



Composite carbon

Plan du procédé GaBi: Mass [kg]
Les noms des procédés de base sont affichés.



Appendix C: Normalized environmental impacts with Environmental Footprint 2.0

The normalization factors are given p.30

The normalized environmental impacts are dimensionless

Impact categories	**2024**	**7175**	**Carbon composite**
Acidification potential	4,83E-04	4,22E-04	1,39E-02
Human toxicity (cancer)	3,27E-04	2,70E-04	2,94E-03
Climate change	9,55E-04	8,88E-04	4,42E-03
Eutrophication freshwater	2,02E-05	2,06E-05	9,40E-05
Eutrophication marine	1,43E-04	1,12E-04	1,34E-02
Eutrophication terrestrial	2,43E-04	2,23E-04	2,34E-02
Ionizing radiation	5,07E-03	5,02E-03	1,06E-02
Land use	5,04E-05	4,72E-05	1,66E-04
Human toxicity (non-cancer)	1,03E-03	7,37E-04	5,98E-03
Ozone depletion potential	2,94E-12	2,97E-12	1,16E-11
Photochemical ozone formation	2,91E-04	2,64E-04	1,64E-02
Resource energy	1,90E-03	1,84E-03	1,00E-02
Resource use minerals and metals	2,42E-03	4,12E-03	7,83E-05
Particulate matter	5,29E-04	4,39E-04	2,37E-03
Ecotoxicity freshwater	-9,58E-05	-1,03E-04	1,74E-04
Water use	9,83E-05	9,04E-05	3,30E-04

Appendix D: Evaluation of uncertainties

Formulas to calculate u(IC_i), note_i and u(note_i) are given p.31.

I. Aluminium alloy 2024

Resources or emissions	Unity	Mean value	Standard deviation %	Standard deviation	Impact category associated	u(IC_i)	note_i	u(note_i)
Acidification	mole of H+	2,68E-02	1,82E+00	4,88E-04	**Acidification**	1,54E-05	5,70E-04	3,28E-07
Human toxicity (cancer)	CTUh	1,26E-08	1,63E+00	2,05E-10	**Human toxicity (cancer)**	6,49E-12	3,67E-04	1,89E-07
Climate change	kg CO2	8,02E+00	1,87E+00	1,50E-01	**Climate change**	4,74E-03	1,11E-03	6,55E-07
Eutrophication freshwater	kg P	1,48E-05	3,07E+00	4,54E-07	**Eutrophication freshwater**	1,44E-08	2,04E-05	1,98E-08
Eutrophication marine	kg N	4,04E-03	2,23E+00	9,01E-05	**Eutrophication marine**	2,85E-06	1,61E-04	1,14E-07
Eutrophication terrestrial	mole of N	4,30E-02	2,22E+00	9,55E-04	**Eutrophication terrestrial**	3,02E-05	2,77E-04	1,94E-07
Ionizing radiation	kBq U235	2,14E+00	1,75E+00	3,75E-02	**Ionizing radiation**	1,18E-03	5,07E-03	2,81E-06
Land use	Pt	7,06E+01	2,85E+00	2,01E+00	**Land use**	6,36E-02	5,80E-05	5,23E-08
Human toxicity (non-cancer	CTUh	4,87E-07	2,46E+00	1,20E-08	**Non-cancer**	3,79E-10	1,04E-03	8,06E-07
Ozone depletion	kg CFC 11	6,89E-14	3,15E+00	2,17E-15	**Ozone depletion**	6,86E-17	3,09E-12	3,08E-15
Photochemical ozone formation	kg NMVOC	1,18E-02	2,11E+00	2,49E-04	**Photochemical ozone formation**	7,87E-06	3,72E-04	2,48E-07
Resource energy	MJ	1,24E+02	2,14E+00	2,65E+00	**Resource energy**	8,39E-02	1,23E-03	8,35E-07
Resource use minerals and metals	kg SB	1,54E-04	5,07E+00	7,81E-06	**Resource use minerals and metals**	2,47E-07	1,57E-03	2,52E-06
Particulate matter	PM2,5	3,80E-07	1,54E+00	5,85E-09	**Particulate matter**	1,85E-10	6,40E-04	3,12E-07
Ecotoxicity freshwater	CTUe	2,03E+00	7,60E-01	1,54E-02	**Ecotoxicity freshwater**	1,00E-03	-1,05E-04	-9,35E-08
Ecotoxicity freshwater	CTUe	9,03E-01	3,07E+00	2,77E-02				
Water	m3	7,18E+03	9,24E-01	6,63E+01	**Water use**	2,97E+00	6,27E-04	1,65E-03
Water	m3	-7,18E+03	-9,24E-01	6,63E+01				

II. Aluminium alloy 7175

Resources or emissions	Unity	Mean value	Standard deviation %	Standard deviation	Impact category associated	u(IC_i)	note_i	u(note_i)
Acidification	mole of H+	2,34E-02	1,93E+00	4,52E-04	**Acidification**	1,43E-05	4,98E-04	3,04E-07
Human toxicity (cancer)	CTUh	1,04E-08	1,63E+00	1,70E-10	**Human toxicity (cancer)**	5,36E-12	3,03E-04	1,56E-07
Climate change	kg CO2	7,46E+00	2,04E+00	1,52E-01	**Climate change**	4,81E-03	1,03E-03	6,65E-07
Eutrophication freshwater	kg P	1,51E-05	3,11E+00	4,70E-07	**Eutrophication freshwater**	1,49E-08	2,08E-05	2,04E-08
Eutrophication marine	kg N	3,17E-03	2,42E+00	7,67E-05	**Eutrophication marine**	2,43E-06	1,27E-04	9,69E-08
Eutrophication terrestrial	mole of N	3,95E-02	2,40E+00	9,48E-04	**Eutrophication terrestrial**	3,00E-05	2,54E-04	1,93E-07
Ionizing radiation	kBq U235	2,12E+00	1,86E+00	3,94E-02	**Ionizing radiation**	1,25E-03	5,02E-03	2,95E-06
Land use	Pt	6,61E+01	3,10E+00	2,05E+00	**Land use**	6,48E-02	5,43E-05	5,32E-08
Human toxicity (non-cancer	CTUh	3,50E-07	2,02E+00	7,07E-09	**Non-cancer**	2,24E-10	7,44E-04	4,75E-07
Ozone depletion	kg CFC 11	6,94E-14	3,24E+00	2,25E-15	**Ozone depletion**	7,11E-17	3,11E-12	3,19E-15
Photochemical ozone formation	kg NMVOC	1,07E-02	2,29E+00	2,45E-04	**Photochemical ozone formation**	7,75E-06	3,37E-04	2,44E-07
Resource energy	MJ	1,20E+02	2,27E+00	2,72E+00	**Resource energy**	8,61E-02	1,19E-03	8,57E-07
Resource use minerals and metals	kg SB	2,62E-04	3,29E+00	8,62E-06	**Resource use minerals and metals**	2,73E-07	2,68E-03	2,79E-06
Particulate matter	PM2,5	3,15E-07	1,32E+00	4,16E-09	**Particulate matter**	1,31E-10	5,31E-04	2,22E-07
Ecotoxicity freshwater	CTUe	1,96E+00	1,02E+00	2,00E-02	**Ecotoxicity freshwater**	8,28E-04	-1,14E-04	-7,72E-08
Ecotoxicity freshwater	CTUe	7,42E-01	2,28E+00	1,69E-02				
Water	m3	6,97E+03	1,10E+00	7,67E+01	**Water use**	3,43E+00	5,77E-04	1,90E-03
Water	m3	-6,97E+03	-1,10E+00	7,67E+01				

III. Carbon composite

Resources or emissions	Unity	Mean value	Standard deviation %	Standard deviation	Impact category associated	u(IC_i)	note_i	u(note_i)
Acidification	mole of H+	7,69E-01	9,75E+00	7,50E-02	**Acidification**	2,37E-03	1,64E-02	4,81E-05
Human toxicity (cancer)	CTUh	8,33E-08	9,21E-01	7,67E-10	**Human toxicity (cancer)**	2,43E-11	3,29E-03	2,14E-06
Climate change	kg CO2	3,30E+01	6,71E+00	2,21E+00	**Climate change**	7,00E-02	5,12E-03	1,08E-05
Eutrophication freshwater	kg P	9,12E-05	6,05E+00	5,52E-06	**Eutrophication freshwater**	1,74E-07	9,49E-05	1,35E-07
Eutrophication marine	kg N	3,79E-01	9,89E+00	3,75E-02	**Eutrophication marine**	1,19E-03	1,51E-02	4,48E-05
Eutrophication terrestrial	mole of N	4,14E+00	9,89E+00	4,09E-01	**Eutrophication terrestrial**	1,29E-02	2,67E-02	7,93E-05
Ionizing radiation	kBq U235	6,43E+00	8,83E+00	5,68E-01	**Ionizing radiation**	1,80E-02	1,06E-02	2,60E-05
Land use	Pt	3,38E+02	8,56E+00	2,89E+01	**Land use**	9,15E-01	1,91E-04	4,44E-07
Human toxicity (non-cancer	CTUh	2,91E-06	1,23E+01	3,58E-07	**Non-cancer**	1,13E-08	6,04E-03	2,33E-05
Ozone depletion	kg CFC 11	3,88E-13	8,06E+00	3,13E-14	**Ozone depletion**	9,89E-16	1,22E-11	2,61E-14
Photochemical ozone formation	kg NMVOC	6,60E-01	9,76E+00	6,44E-02	**Photochemical ozone formation**	2,04E-03	2,09E-02	6,12E-05
Resource energy	MJ	6,16E+02	6,83E+00	4,21E+01	**Resource energy**	1,33E+00	6,49E-03	1,35E-05
Resource use minerals and metals	kg SB	6,40E-06	7,79E+00	4,99E-07	**Resource use minerals and metals**	1,58E-08	5,09E-05	1,07E-07
Particulate matter	PM2,5	1,64E-06	9,98E+00	1,64E-07	**Particulate matter**	5,18E-09	2,86E-03	7,72E-06
Ecotoxicity freshwater	CTUe	1,00E+00	0,00E+00	0,00E+00	**Ecotoxicity freshwater**	3,58E-3	3,19E-04	9,85E-07
Ecotoxicity freshwater	CTUe	2,05E+00	5,52E+00	1,13E-01				
Water	m3	8,16E+03	9,07E+00	7,40E+02	**Water use**	3,31E+1	2,11E-03	1,09E-2
Water	m3	-8,16E+03	-9,07E+00	7,40E+02				