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Primary data-based life cycle assessment of automotive hybrid materials

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Graz, February 2017

Declaration of academic integrity

I hereby declare that this master thesis has been written only by the undersigned and without any assistance from third parties.
Furthermore, I confirm that no sources have been used in the preparation of this thesis other than those indicated in the thesis itself.

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Abstract

Magna Steyr, a leading tier-1 automotive supplier and automobile manufacturer, has chosen to analyse and assess the environmental impacts of two different composite hybrid materials and compare them with a conventionally built body part. Within the scope of a pre-feasibility project, a classic aluminium-made cross beam located in the rear area of the roof served as a benchmark and was compared to two alternative constructions using a thermoset/aluminium hybrid material. The life cycle assessment has been carried out in a cradle-to-grave manner, meaning to analyse the environmental impact from the production of raw materials, the use phase and the end-of-life-phase including recycling, landfilling or waste incineration with thermal dissipation. The indicators of interest included resource use, greenhouse gas emissions, water footprint and land use, depending on the available data.

The gathering and collection of data is the most time-consuming part of a life cycle assessment in case of primary data-based assessments. In addition to primary data made available from several different suppliers, datasets from ecoinvent, USLCI and EULCI databases were used to fill in the gaps that could not be filled by Magna’s suppliers. The modelling of the processes and the calculation of the impacts was done using Pré’s SimaPro software. The goal of this LCA was to assess not only the above-mentioned indicators in different impact categories, but also to analyse uncertainty that goes along with the production of a life cycle assessment that deals with new material combinations. A sensitivity analysis has been carried out as well to learn about important variables.

In the conclusion, the influence of LCAs in entrepreneurial decision-making processes is discussed based on expert interviews to explore possibilities and limits. Future goals have been derived to promote the implementation of future LCAs.

Abstract

Diese Masterarbeit beschäftigt sich mit der vergleichenden Untersuchung der Umweltauswirkungen von Produkten, die von Magna Steyr, einem führenden automotiven Tier-1 Lieferanten und Produzenten, hergestellt werden. Forschungsgegenstand der Arbeit ist ein hinterer Heckquerträger, welcher mit zwei Leichtbaualternativen verglichen wurde. Während die Basisvariante vollständig aus Aluminium besteht, basieren die alternativen Konstruktionen jeweils auf einer Paarung aus Aluminium und kohlefaserverstärkten Kunststoffen. Die Ökobilanz wurde vollumfänglich von der Wiege bis zur Bahre durchgeführt. Das bedeutet, dass sämtliche Umweltauswirkungen über den gesamten Lebensweg von der Rohstoffgewinnung, Herstellung, Nutzungsphase und Beseitigung ermittelt wurden. Fokus lag dabei auf den Kernindikatoren Ressourcenverbrauch, Treibhausgasemissionen, Wasserfußabdruck und Flächenverbrauch.

Die Sammlung von Daten zur Modellierung ist der zeitintensivste Teil einer Ökobilanz und wurde daher in einem frühen Stadium der Bilanzierung gestartet. Da es nicht immer möglich ist, genaue Informationen von Lieferanten zu erhalten, wurden Datenlücken durch Bestandsdaten aus der Ecoinvent, der USLCI- sowie der EULCI-Datenbank gefüllt. Zur Bewertung der Auswirkungen wurde SimaPro von Pré verwendet. Neben der Ermittlung von Umweltauswirkungen wurde sowohl eine Unsicherheits- als auch eine Sensitivitätsanalyse durchgeführt, um Unsicherheiten primärdatenbasierten Ökobilanzen und Methoden dazu zu bewerten und wichtigste Einflussfaktoren zu klassifizieren.

Abschließend wurde der Einfluss von Ökobilanzen in unternehmerische Entscheidungsprozesse untersucht. Dafür wurden Fachinterviews innerhalb des Engineerings bei Magna Steyr durchgeführt, um Möglichkeiten und Grenzen von Ökobilanzen im Unternehmen zu bewerten. Zukünftige Ziele und Anforderungen wurden definiert, die sowohl Durchführung als auch Integration von LCAs im Unternehmen fördern können.

Abstract

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By

Henning Sommer

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List of abbreviations

ACL	Anti-corrosive layer
BIW	Body in white
CDP	Cataphoretic dip painting
CF-	Carbon fibre-
CFRP	Carbon fibre reinforced polymers
CML	Center for Environmental Sciences, The Netherlands
ELCD	European Reference Life Cycle Database
ELV	End of life vehicle
EOL	End of life
EPA	United States Environmental Protection Agency
FRV	Fuel reduction value
GF	Glass fibre
GFRP	Glass fibre reinforced polymers
IPCC	International Panel on Climate Change
IPP	Integrated product policy
ISIS	Institute for System Sciences, Innovation and Sustainability Research
kW	Kilowatt
kWh	Kilowatt hour
LC	Life cycle
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle inventory assessment
MJ	Mega joule
MS	Magna Steyr
MSE-AUT	Magna Steyr Engineering Centre, Austria
MVEG	Motor Vehicle Emissions Group
OEM	Original equipment manufacturer
PDF	Potential disappeared fraction
Preform	Preformed component
Prepreg	Preimpregnated component
rCF	Recycled carbon fibre
ReCiPe	Methodology for life cycle assessment by RIVM, CML, PRé consultants
SMC	Sheet moulding compound
TECABS	Technologies for Carbon Fibre Reinforced Modular Automotive Body Structures
USLCI	US Life Cycle Inventory Database
vCF	Virgin carbon fibre
VW	Volkswagen

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Acknowledgement

This master thesis has been conducted in collaboration with Magna Steyr Engineering Center Austria and the institute of sustainability and innovation science (ISIS) in Graz, Austria. This project was performed in the environmental compliance group involved in a pre-feasibility phase project within Magna Steyr.

This work has been supervised by Univ.-Prof. Dr. Rupert Baumgartner and MSc. Josef Schöggl of the ISIS Graz. I would like to use this opportunity to thank both for their supporting role in the development of this thesis and the help they have given me to conduct such an assessment.

I would also like to thank the participating personnel at Magna Steyr, namely DI Dietmar Hofer, the senior environmental officer and DI Stefan Kaufmann, the development engineer in composite compounds at Magna Steyr. Without their help, a realisation of this assessment would not have been possible. Their experience and competence have been a very helpful element in the research process of my thesis.

Graz, February 2017
Henning Sommer

1. Introduction

1.1. Motivation

On the 7th February 2001, the European Commission presented its Green Paper on Integrated Product Policy (IPP) (Commission of the European Communities, 2001). An essential characteristic of IPP is the assessment of the whole life cycle of a product. A very important decision is being made during the product design process, in which all the necessary steps regarding production, use and recycling of products must be considered. This holistic approach shall guarantee an abatement of environmental damages and an increase of environmental benefits at every single stage of a product's lifecycle. A second important requirement is the production and dissemination of information on the environmental burden of a product. Only if the environmental impacts are known, more environmentally friendly products can be developed.

Simultaneously, environmental information of products shall help customers in their purchase decision based upon these environmental aspects. Companies pursue to assess and lower environmental impacts through sustainable evolutionary product development using several different methods within the product life cycle management (Magna International Inc., 2016). To understand the ecological footprint and to take responsibility, the ecodesign approach is a method that is applied within early stages of product development. This approach encourages product designers to actively design products in a way such that they provide a benefit to the customer at the lowest environmental cost (Luttropp & Lagerstedt, 2006, p. 1397). This means that the designer not only needs to consider the whole product life cycle, but also requires technical and environmental knowledge to be implemented in the product design phase (Lagerstedt, 2003). While the concept of ecodesign is understood as the greater approach, life cycle assessment represents a tool to put improvement strategies into motion.

Fig. 1 depicts the influence of the ecodesign approach within different stages of the product design phase until its use phase and shows the possible reductions of the environmental burdens depending on the stage at which it is integrated in the development. It becomes clear that there are only few options to reduce environmental impacts during the use phase, because important decisions regarding material choices and production techniques as well as material suppliers for the product have been defined in earlier stages of the product life. These decisions can be made during feasibility phases, at which the possible impact reduction is much higher. While Fig. 1 sketches this relation in context of the automotive industry for the sake of this study, it can nevertheless be transposed to other branches and industries.

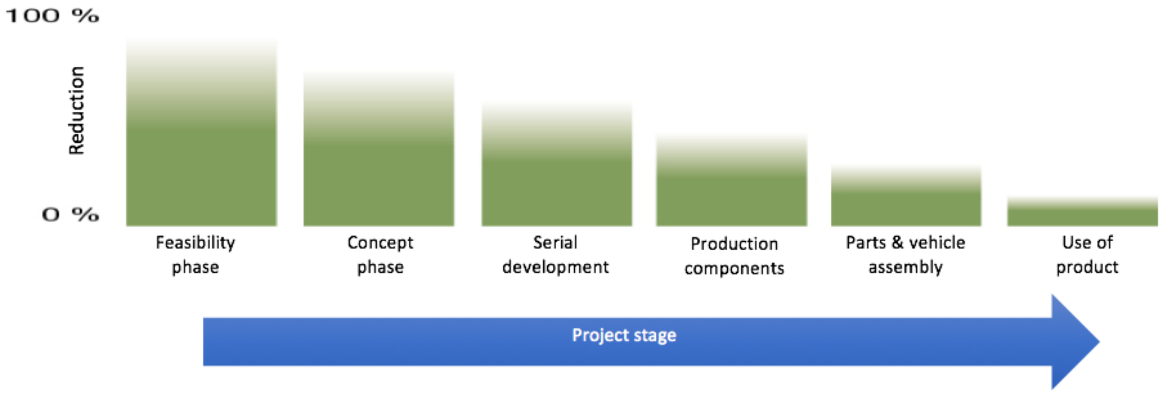

Fig. 1: Possible influence of ecodesign along different product development stages (Magna Balance CO2DE).

Companies have a strategic intent in which they state the scope of their business. Classic goals of companies according to the common knowledge of business administration are high productivity or the maximization of the shareholder value (Copeland et al., 1994, p. 97ff). Others may define their aim in delivering goods to customers satisfying their individual needs. Along with the constantly increasing number of products and production capacity comes an increase of resource use and emissions to the environment. Companies have learned about rising emissions into air, land and sea. They have also learned that customers have an increasing interest in the environmental impacts and compare them to other products of the same category, demanding companies to reduce environmental impacts of their products (Johansson, 2002, p. 98). At the end of the 1960’s, Coca-Cola was the first ever company to assess and analyse the environmental impacts of their drinking bottles (Hunt & Franklin, 1996, p. 1). They commissioned the first study to examine the product related impact of packaging and started a movement that quickly got other companies into assessing their products and comparing it to others. Since then, the method of life cycle assessment has become a widespread tool for the assessment, analysis and interpretation of product emissions.

The awareness of the importance of environmental protection and the possible impacts associated with products, both manufactured and consumed, increased the interest in the development to better understand these impacts (International Standardization Organisation, 2006). Products are created because they satisfy a need. Each product has a life that begins with the design. This is followed by resource extraction, the production of semi-finished products, components and the final product. The use phase satisfies the initial need for the product, until it reaches the end-of-life phase in which it is being recycled, incinerated or dumped on landfills. All phases of product life have a direct or indirect effect on the environment due to the use of resources, emission of substances or other exchanges with the environment.

With the establishment of life cycle thinking and an increasing awareness of environmental impacts, life cycle assessment has become increasingly prevalent in the past three decades (Life Cycle Initiative, 2016). This life cycle thinking can be understood as the framework, including a set of tools and approaches that focus on the interdependencies of a product with the environment. This variety of tools include life cycle assessment, an approach to assess environmental impacts of a product at different stages of its life (Klöpfer, 1997). Another technique is life cycle management, which is an approach used in businesses to manage the total life cycle of the goods, products and services this business is offering (Hunkeler, et al., 2003). Life cycle costing analyses the total cost of a given process, system or product over its life cycle to eventually determine the most cost-effective way to deliver a specific service or product (Woodward, 1997). Integrated product policy seeks to reduce the environmental burden of products throughout their life cycle by involving all stakeholders to improve the environmental performance of products on a life cycle scale (Charter, 2001). The life cycle thinking allows to assess how product consumption and environmental impacts are related to each other, at which not a single product is evaluated but a holistic approach is pursued. The research is not limited to the individual product, but how this product is consumed.

The life cycle thinking approach means leaving the focus on manufacturing site and process to learn about impacts related to a certain product or production site (Life Cycle Initiative, 2016). The goal behind life cycle thinking is to gradually reduce resource intensity as well as ecologic and ultimately economic performance of a product throughout its whole life cycle. Entrepreneurial thinking thus must also focus on up- and downstream processes during the manufacture of a product.

Fig. 2 (Rebitzer, 2004, p. 702) below is a simplified representation of the entire product life and usually referred to as the life cycle of a product. It not only includes the actual product life, but also represents imminent relationships with the environment, represented by loops between the actual life stages. It is visible that products have stand in interaction with the environment at every step in their life, and that a recycling strategy is essential to regain valuable resources after the product's life has ended. This complete life cycle is assessed in a life cycle analysis.

The design and development phase offers the greatest opportunities to reduce product-related environmental impacts, enabling product designers to create a strategy before the actual production has even started. This minimizes product environmental impacts through minimum use of material, respecting all current laws, material restrictions, best practice approaches, and standards. This results in a more environmental friendly product not only in the use phase, but also making its footprint as small as possible during recycling and disposal, translating to a well-balanced recyclability of the raw materials. The use phase is very dependent on the individual use of a product, which leads very little opportunities to influence its impact other than an environmental-friendly design in the first place. The end of life phase has a great impact and potential, which is why a design for recycling and reuse must be considered if a closed loop should be achieved.

This closed loop, in which products and partial products are recycled practically infinitely often, allowing them to be used during a much longer timescale, must be an ecopolitical goal. It not only allows the for the least amount of required material but also a reduced primary energy input. A perfect ecodesign product has a cradle-to-cradle life cycle, resulting in zero waste apart from products that are required during the use phase.

However, it should be mentioned that a product's footprint, calculated by means of a life cycle assessment, not necessarily reveals information about possible environmental-friendliness. A product, say a plastic bag of polyethylene or polypropylene, can have a low carbon footprint, which does not automatically go hand in hand with low environmental burden, as it takes between 100 to 500 years for plastic bags to decay (Deutsche Umwelthilfe e.V., 2016).

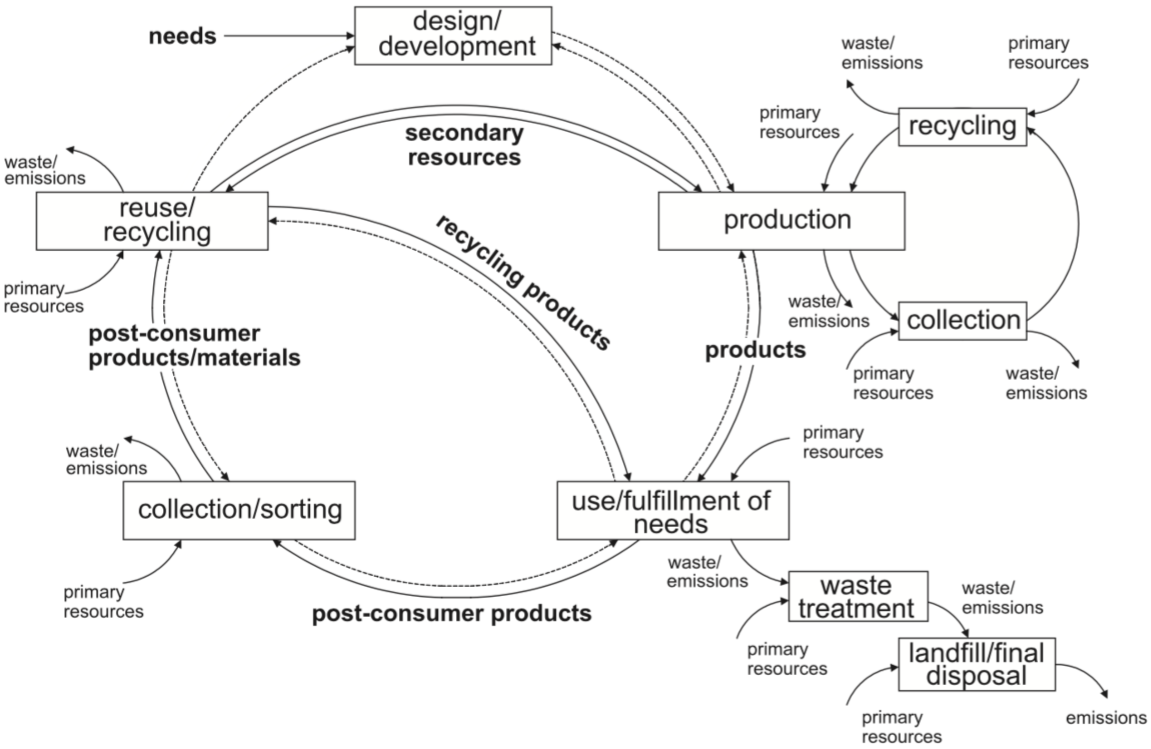

Fig. 2: Feedback loops in Life Cycle Assessment (Rebitzer et al., 2004, p. 702).

Life cycle assessment can thus be considered a tool putting life cycle thinking into practice. The life cycle assessment can be an essential tool when:

- Main environmental impacts of a product during a given life cycle shall be analysed.
- The environmental performance of a product or a process at any given point in their life cycle shall be improved.
- Decision makers in industry, government or non-government organizations shall be provided with information and recommendations.
- Environmental impacts shall be selected and improved.
- Environmental friendly aspects of a product shall be emphasized in marketing and communication.

With help of life cycle assessment, product manufactures gain information about their products, which – depending on the scope of the life cycle assessment – extent from cradle to grave. A highly precise amount of information of paramount importance can be gained in the production of an automotive LCA:

- Used resources,
- Manufacturing of materials,
- Vehicle and component production,
- Fuel production,
- Use phase,
- End of life treatment scenarios, re-use and recycling.

The goal of a complete life cycle assessment is to derive environmental impacts from resource use (this could be primary resources, electricity, materials from the technosphere etc.) and emissions throughout the production phase, the use phase and the end-of-life phase.

A life cycle assessment represents a systematic analysis of environmental impacts of products during the whole life cycle, which in the automotive sector usually comprises a life cycle distance of 150.000 miles/240.000 km (Grundler, 2016). This not only comprehends the full assessment of resource extraction from the earth, but also considers energy expenditures, raw materials and supplies, and emissions into air, land and sea during the production and use phase of the vehicle. The expected information gain comprises, but is not limited to, the components as displayed in table 1 and represents an aggregation of some of the key aspects of environmental-friendly product development.

Table 1: Aspects and goals of life cycle assessments (Own work based on Stradner & Hofer, 2013; Friedrich et al., 2013; European Environment Agency, 1997).

Aspect	Goal
Resource conservation (human, material, energetic)	Minimizing resource intensity and waste production
Weight management	Putting into motion a downward weight spiral by lowering weight of multiple individual parts
Efficient investment park	Short invest payback
Economic mobility	Reduced total cost of ownership
Sustainable mobility	Advantages of alternative propulsion technologies
Sustainable development	Use of renewable resources and recycled materials
Research and development	Material and technology substitution

To assess environmental impacts that go along with the production of an automotive product, Magna Steyr has decided to conduct a life cycle assessment within a prefeasibility project. This is done to learn about potential impacts in the earliest stages in product development. The object of research will be presented in the following upcoming section, along with a description of the problem statement and a definition of the research gap which this thesis seeks to fill.

1.2. Problem statement / research gap

Magna Steyr finds itself in a special role within the automotive sector. As such, Magna Steyr does not act as a classic original end user manufacturer (OEM), but their range of business extends from manual and small volume manufacturing to mid-size and high volume serial production, research and development as well as complete vehicle development. As such, Magna Steyr plays the role of a tier-0,5 supplier for the automotive industry. As the term indicates, tier-0,5 and tier-1 companies produce directly to a company. Other suppliers can deliver to tier-1-companies, making them a tier-2-company to the original end user manufacturer.

The ISO EN 14040 standard for life cycle assessment is part of the ISO 14000 family of standards for environmental management. This specification defines the fundamental framework of components that need to be included in life cycle assessments. However, it leaves a certain degree of freedom to the practitioner, e.g. methods and indicators that are applied in the assessment. In the automotive industry, suppliers usually lay their focus on a simplified input/output analysis as basis for a life cycle assessment (Hofer, D., 2016). And whats more, life cycle assessments are often carried out by service providers specialized in the assessment of environmental impacts.

Within the supplying industry, cooperative development including their respective responsibilities are clearly defined. It is consequently not necesarily in the supplier’s interest to optimize an OEM’s product related environmental impacts, since it is not the classic business case for tier-1-suppliers. Unless the OEM orders the assessment of environmental impacts of a product, e.g. within the scope of a business case, LCAs are usually not carried out. Often, they do not possess the means to assess these impacts, not to mention that in most cases they are occupied with the manufacturing of a pre-designed product with little to no influence on its final design unless these terms have clearly been stated in their contractual basis (Hofer D. , 2016).

The IATF 16949, an international technical specification combining several standards, stipulates a continuous improvement to all companies that submit to the standard (International Automotive Task Force, 2016, p. 81). The focus is set on the improvement of system and process quality as well as the examination of corrective and preventive measures in terms of their effectiveness. This means that OEMs and suppliers alike must take measures to increase the overall performance of their products, which eventually includes the improvement of environmental aspects based on LCA.

In recent years, life cycle assessment has become an increasingly widespread tool which allows producers to gain accurate information on the problems associated with their product related environmental impacts. The information content of the LCA depends largely on three factors (Heijungs, Hellweg, & Koehler, 2009; ISO 14040, 2009):

- The considered scope of the LCA (for example: cradle-to-grave, cradle-to-gate or gate-to-gate),
- The indicators examined considering resources and impacts to air, soil and water, and the human being as well as flora and fauna,
- The quality of life cycle inventory (LCI) data and their origin (primary data, literature data or database).

Depending on interest and subject of investigation, manufacturers define the framework of their life cycle assessment more or less all-encompassing. In accordance to the main ISO 14040ff framework, the most exhaustive LCA is designed from cradle-to-grave and usually considers the product's greenhouse gas emissions in CO_2 equivalents from manufacturing to disposal, required primary energy and resource use. As the studies in chapter 3 will show, most LCAs reduce their investigative spectrum to these three impact categories, leaving out prominent aspects, e.g. impacts on human health, land use or water footprints.

With numerous studies analysing the above-mentioned categories using Cumulative Energy Demand or IPCC 2013 GWP 100a methods (Raugei et al., 2015; Bauer et al. 2015; Boland et al., 2015; Mayyas et al., 2012; Sun et al., 2016), and a lot of studies that deal with the assessment of environmental impacts using other methods such as CML (Maretta et al., 2012, pp. 61-66), ReCiPe (La Rosa et al., 2013, pp. 17-25) and EcoIndicator 99 (Duflou et al., 2009, pp. 9-12), practically none of the studies dealing with lightweight hybrid materials calculate water footprints or land use. This is partly owed to the difficulty in the assessment of these impacts and the lack of available data in ecoinvent or GaBi databases. Finkbeiner and Berger (2010, pp. 919-944), Bayart et al. (2015, pp. 965-879), and Hoekstra et al. (2011, pp. 46-51) have done a great deal of work to develop and implement methods for water footprinting in LCA with Berger et al. producing a study on the water footprint of several Volkswagen (VW) vehicles, which is presented in this thesis later on. Schmidt et al. created a framework modelling indirect land use changes in LCA (2015, pp. 230-238).

From theses aspects, there is an interest to integrate other indicators in the analysis beyond the usual greenhouse gas effects or resource depletion, which may not be negligible from the impact point of view. Judging from the perspective of the tier-1 supplier of automotive components, there is a lack of information on the environmental impact of products in terms of water and land use in addition to already mentioned aspects. The research process on which this thesis is based on has shown that there is a significant lack of studies produced by tier-1 suppliers such as Magna, Bosch, Continental or Grupo Antolin, yet it can only be guessed whether they do not carry out life cycle assessments or they refrain from publishing their studies.

LCA is a very powerful tool to visualize the whole life cycle of a product, besides the assessment of inventory and impacts. The more detailed an LCA in terms of data quality and amounts of data from actual manufacturing processes instead of database values, the more sensitive this LCA becomes as it contains the potential to reveal critical company secrets to competitors. The research process has shown that especially OEMs are very careful at publishing full cradle-to-grave LCAs because they can have the potential – if done in appropriate quality and detail – to be “reverse-engineered” in terms of product manufacturing.

The environmental compliance department within Magna Steyr in Graz considers the life cycle assessment as a very important tool to gain important knowledge about product related environmental impacts on one hand and as a very effective approach to find improvements for current and future production techniques, material choices and marketing strategies on the other hand.

The new setting in this LCA is to identify the aforementioned indicators (carbon footprint, water footprint, land use) for two lightweight hybrid concepts with conventional construction and compare them to a benchmark material concept. Furthermore, the novelty is to carry out an LCA by introduction of the new simulation tool SimaPro 8 at Magna Steyr.

The analysis compares two hybrid composite materials to a benchmark material made of aluminium. The hybrid materials are made of a combination of aluminium and carbon-fibre reinforced plastics and recycled carbon-fibre reinforced plastics respectively. The life cycle assessment method following the ISO EN 14040 standard was used to find answers to the following questions within a comparative LCA:

- What are the environmental impacts over the complete life cycle of the aluminium benchmark material from resource extraction, use phase and recycling?
- Which environmental impacts can be expected from the hybrid material concepts?
- How much better or worse are environmental impacts of the hybrid material concepts compared to the benchmark material?
- Are exploitable data regarding the land and water use available?

In addition to that, the assessment of studies has shown that life cycle assessments represent a topic that is not widely embraced in current literature regarding a deeper inspection of different end-of-life-treatments and new material combinations such as the materials assessed in this thesis. Most of the studies that have been assessed in this thesis only assume a conventional end-of-life-treatment, e.g. co-incineration of carbon fibres. Das (2011) produced an exhaustive study providing a set of different recycling approaches, which shows that alternatives to co-incineration exist, which will be presented in chapter three. It has also come to the author’s attention that most LCAs within the automotive sector are carried out in a cradle-to-grave manner, but often using only a few indictors such as carbon footprint and primary energy use, even though a wide range of data was available. This will also be presented in the assessment of studies in the automotive sector in chapter three.

Studies assessed prior to this work have also shown that the topics of uncertainty and sensitivity analysis are widely underrepresented in current literature and research studies, even though they are an essential aspect in life cycle assessments by means of their validity and expressiveness (Heijungs, Hellweg, & Koehler, 2009). Current tools for life cycle assessment have become very supportive, and make it easy for the practitioner to calculate uncertainty values or manipulate certain values during the assessment to learn about possible weaknesses and aspects that have great impacts to the results of the model, yet these methods are rarely used in life cycle assessment, which why this thesis also seeks to answer the following questions:

- How prone to uncertainty are primary data-based life cycle assessments and what methods exist to assess uncertainty in life cycle analysis?
- How comprehensive are database data regarding land use and water footprint information?
- What are limits of life cycle assessments and the results thereof within the scope of corporate decision making?

The object of research in this life cycle assessment (LCA) is a roof cross member which is situated in the back of the roof of an estate car. It is an important structural component in the body of a vehicle providing stability, making the body buckling resistant and, in addition, houses the hinge for the trunk lid. The automotive part is described in detail in chapter 4.

Cross beams represent an interesting approach for weight reductions in the general roof construction of vehicles because they have traditionally been built using steel sheets. Aluminium sheets and alloys have only recently been introduced into the use for components. Weight reduction in this area can result in a lowering of the total centre of mass, resulting in enhanced vehicle dynamics and stability. The choice to analyse carbon fibre reinforced polymer (CFRP) components to replace or go with aluminium parts is due to several aspects:

- CFRPs have high stability and torsion stiffness which means the carrying metal sheet can be reduced in thickness.

- CFRPs can be produced in many different shapes and sizes which can be perfectly integrated into existing body and chassis structures.
- CFRPs have a high potential for functional integration, allowing for more design freedom, e.g. making it easy to prepare pockets for metal inserts or accommodate other functions in one part.
- CFRPs can be integrated into the vehicle body using multiple different joining technologies. They can either be pressed, clued or screwed into or onto existing body parts.
- With the application of CFRP, a lightweight spiral can be set into motion. E.g. while one roof cross member weighs around 7 kg using aluminium, the weight can be reduced to about 5,4 kg using a combination of aluminium and CFRP. This may not sound much, but keeping in mind that a roof construction consists of up to four cross members, there is significant weight reduction potential having direct effect on vehicle dynamics.

However, the application of CFRPs is also faced with considerable challenges. Above all, the high-energy input in the production of the polyacrylonitrile-based (PAN) precursor and the actual fibre-reinforced polymer seem to interfere with a mass application of carbon-fibre reinforced plastics. In addition, there is currently no uniform and ideal recycling process available that allows the recovery of undamaged fibres on an industrial scale. The many approaches that are pursued in different studies are partly promising, but require further research and are still partially located in the laboratory scale (Pimenta & Pinho, 2015). The results of this LCA will serve as a further basis in the decision making within the scope of future material choices at Magna Steyr.

To illustrate the theoretical concept of life cycle assessments, chapter two begins with a general overview about the formal steps in such an assessment with the different phases according to ISO 14040 and ISO 14044. It also presents the methods which have been used in this life cycle assessment, followed by an introduction into the two concepts of classic attributional life cycle assessment and the consequential life cycle assessment.

The third chapter picks up at the end of the second chapter and gives an overview about the current state of LCA within the automotive industry and gives an insight into the common practice of LCA regarding lightweight materials, hybrid materials and multi-body vehicle design. It points out the variability of these studies as well as areas for improvement and shows the deficit of many LCAs, meaning that most LCAs set their focus on only a few indicators and impact categories with often very superficial end-of-life scenarios and lacking an uncertainty analysis.

The fourth chapter consists of the actual comparative life cycle assessment of the parts using SimaPro 8.2 as modelling software, including several inventory databases such as the Ecoinvent 3.2 database. Goal and scope of the LCA are defined in this chapter, followed by the inventory analysis, the impact assessment and the interpretation per ISO EN 14040 environmental management – life cycle assessment standard.

The fifth chapter includes a discussion concerning the variability of the results of this LCA and an overview about future goals in LCA. Furthermore, it gives answers to questions regarding comprehensiveness of databases and methods for the uncertainty and sensitivity analysis. Furthermore, interviews that have been conducted at Magna with department heads, project managers, engineers and developers (cf. p. 137) to find answers to the question of limits of LCAs and their results in corporate decision making.

Finally, a conclusion follows in the sixth chapter, paired with an outlook for possible future developments and a definition of future requirements to eventually ease the general life cycle assessment to make LCA a more common tool for industry and development. All information regarding parameter settings and process information is provided within the SimaPro 8.2 product model. The inventory is appended in the annex of this thesis.

2. Theoretical concept of LCA

Depending on its goal and scope definition, a life cycle assessment can address a wide range of environmental aspects. General attributional life cycle studies usually consider resource use, energy use or greenhouse gas emissions during the production and use phase as well as the recycling phase of a product. The procedure of an LCA has been standardised by the International Organization for Standardization and put into a standard named ISO 14040 (DIN Deutsches Institut für Normung e.V., 2009). It is thus integrated into the environmental management standards. The core principal of a life cycle assessment has always been that the environmental impact of a product or service must be assessed from cradle to grave, meaning from raw material acquisition through production, use and end of life treatment, recycling and final disposal. Each of those stages entails some degree of environmental impact, either in terms of resource depletion, emissions or any other indicators used in the assessment. The term attributional indicates that each component of a product entailing an environmental impact is attributed to that impact (causality principle).

The ISO 14040 defines four phases in an LCA studies, outlining the necessary steps in a formal life cycle assessment. This methodology will be described to point out the appropriate usage for the automotive sector. In contrast, the ISO 14044 is far more comprehensive and provides requirements and guidance, and describes the additional tasks to be performed when a life cycle assessments are intended to be published.

Another variant of life cycle assessments is the well-to-wheel-analysis. This is a specific assessment which is commonly used to assess overall efficiency of fuel supply from the production, processing and transport of fuel as well as the energy conversion efficiency. Furthermore, this approach can be used to compare the impact of alternative propulsion techniques, including the fuels used in the different transport modes and the respective carbon footprint (MacLean & Lave, 2003). This assessment can be broken down into the subdivisions of well-to-tank analysis, assessing the fuel supply, and tank-to-wheel, assessing the driving efficiency of the vehicle. Well-to-wheel assessments are very specific to a vehicle, answering questions regarding the efficiency of the propulsion and thereby leaving out environmental impacts caused by the production, use and end of life of an automotive product. A well-wheel-analysis has thus not been carried out within this thesis.

2.1. Steps in a formal LCA

2.1.1. Goal and scope

The ISO 14040 standard defines, amongst two others, two main requirements for the goal definition:

- The application and intended audience shall be described unambiguously. This is important since a study that aims to provide data that will be used internally compared to a study that aims to make comparisons between two products public. For example, in the latter case ISO states that weighting may not be used in impact assessment and that a peer review process is necessary. It is therefore important to communicate with the stakeholders during the execution of the study.
- The reasons for carrying out the study should be clearly described. Is the commissioner or practitioner trying to prove something or is the commissioner intending to provide information only?

The goal and scope definition are the first steps within a life cycle assessment. It is also the most important part in the assessment. The researches might want to know the general environmental impacts of a vehicle, or what changes in impact a different material design can lead to. The goal should give a clear description of what questions the study aims to answer. It should also define the intended audience, whether it be a client from a company, from a public institution or a public audience.

Next to the goal definition comes the definition of the functional unit. The ISO 14040 states that the purpose of the functional unit is to provide a reference to which the inventory data are related to ensure alternatives are compared on a common basis. Every system that is being compared in the LCA has to meet the demands of the functional unit. For automotive parts, for example, the benefits in terms of safety, functionality etc. must be the same in every compared scenario. This is exactly defined by the functional unit, applying for all compared variants. Along with this requirement the total amount of product to meet this demand is known as the reference flow. By modelling the corresponding system, the reference flow includes precise information about energy flows, type and quantity of materials as well as the number of times a material has to be replaced during its life cycle or the timeframe specified within the LCA.

2.1.2. Inventory analysis

The second step in an LCA is modelling a product life cycle with all the environmental inputs and outputs. This step is known as the life cycle inventory (LCI). The inventory analysis (IA) covers the collection and modelling of data. The available information flows into a calculation diagram, which shows all inputs and outputs. The quality of the data is of great importance since the calculation of the product impact depends exclusively on the available data and should be cross checked from several sources if possible. After the IA step, the researcher should have all the information on the product process and have available figures for total emissions, energy consumption and resource consumption throughout the flowchart.

While the creation of the inventory analysis has been carried out manually for a long time, the creation of such an inventory by various software tools is no longer a difficult task. The most common software solutions SimaPro and GaBi allow users to create inventories using the information they collected or from databases which have been integrated in the modelling software. SimaPro for example integrates several versions of the Ecoinvent database in its software, allowing the user to easily build their products from readily available data. These databases have been compiled for many years by research companies or in collaboration with several companies and governments which submit their process and product information to these databases. These often national and regional databases can be very specific and sometimes focus on certain industrial branches, e.g. the Danish database of environmental impacts from basic food products or the German PROBAS database. Others can be very exhaustive and include various datasets of many different areas, such as the Ecoinvent Database or the European Reference Life Cycle Database (ELCD). If life cycle assessments shall be carried out using only primary data from generic processes, researchers must create their own process data in order to model their specific processes (Heijungs, Hellweg, & Koehler, 2009).

2.1.3. Impact analysis

Finally, after all necessary product related data have been gathered, the next step in LCA is to calculate and assess the environmental impact. There are different concepts and methods available for this impact assessment. The goal behind the impact assessment is not only to bring all the process data into numbers, but also make the results of LCA easier to commute and comprehend. It is important to mention that impact assessment methods only cover a certain, pre-defined amount of impacts. To give the full picture of potential impacts, the practitioner may be forced to apply several different methods if multiple impact categories were to be assessed which may not be included in one single method. Table two presents a short overview about a few different methods, showing amongst others the dimension, the assessment unit and the result of the respective method to illustrate the possible requirement to use more than one impact assessment method. In the impact assessment of an LCA, the steps are as follows:

- Selection of the impact categories
- Classification of the inventory results
- Characterization of the impact in each category
- Analysis such as *weighting* and *normalization* of impacts to establish comparability to other and showing how they relate to each other respectively

While the two steps *classification* and *characterization* are mandatory, *weighting* and *normalization* are optional. Normalization allows to put the impact estimates into an appropriate context to a given baseline, making them easier to grasp in form and content. Weighting allows the decision maker to see which impacts are more important by assigning weights to these impacts, enhancing decision making and pointing out important differences when two products of the same kind are being compared. There are several different methods that can be applied in LCA depending on the impact categories of interest, the geographical focus and the calculation method.

The assessment methods differ in several aspects because they are applied in different areas and different units are used for assessment. Furthermore, in some methods, the practitioner has the choice between midpoint and endpoint assessment, which differ in the approach of the damage assessment. Midpoint is generally understood to be the problem-oriented approach which indicates possible factors that can cause or generate damage. These can, for example, influence climate change or the acidification potential of the materials and substances studied. In contrast, there are endpoint methods that show the impact on humans, the environment, or nature. Endpoint methods are referred to as damage-oriented and include, for example, the possible deaths caused by increased concentrations of chemicals in water bodies as shown in Fig. 3. In this case, damage-oriented means the possible damage an object of protection can be subject to. Simplified, a midpoint method looks at the possible damages in the middle of the cause-effect-chain, while an endpoint method looks at the end of the cause-effect-chain (Pré Consultants bv, 2014).

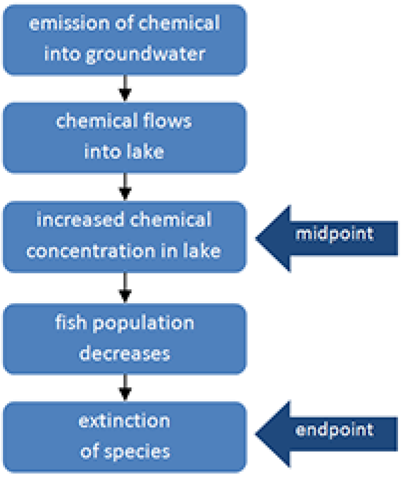

Fig. 3: Different stages at the cause-effect-chain (Pré-Sustainability, 2014).

The following table 2 shows an excerpt of a few popular methods for the inventory and impact assessment respectively.

Table 2: Inventory and Impact assessment methods in Life Cycle Assessment (Pré Consultants bv, 2016).

Method	**Geographical restriction**	**Application**	**Dimension**	**Assessment Unit**	**Result**
CML (midpoint)	Europe	Impact analysis	Multi-dimensional	Material + energy flux	Multi-dimensional profile per material and energy flux
Cumulative Energy Demand	International	Inventory analysis	Single-dimensional	Energy intensity	Performance figure: Energy demand
Ecologic Scarcity	International	Impact analysis	Single-dimensional aggregated	Material and energy flows in differentiated Input and Output	Performance figure: Environmental Burden Points ("Umwelt-belastungs-punkte")
ReCiPe Individualist (i), hierarchist (h), egalitarian (e) (midpoint, endpoint)	Europe	Impact analysis	Multi-dimensional aggregated	18 different impact categories, 3 endpoint indicators	Aggregated endpoint categories: Human health, Ecosystems, Resource Surplus Costs
Water footprint (Hoekstra)	International	Impact analysis	Single-dimensional	Consumption-to-availability-ratio CTA	Water scarcity index WSI
Impact 2002+ (midpoint, endpoint)	Europe	Impact analysis	Multi-dimensional	14 different midpoint impact categories, 4 endpoint impact categories	Damage Aggregated endpoint categories: Human Health, Ecosystem Quality, Climate Change, Resources

The appropriate method is chosen with respect to the required outputs of the goals of the study. For each type of impact assessment, material and energy flows from the inventory analysis are assigned to various categories of environmental effects (classification) and then converted into an action indicator which has been established by scientific models (characterization). So, all global warming emissions of a product system are summarized, for example, for the assessment of the impact on climate change. Each substance contributing to an impact category can be multiplied by a characterization factor to express the relative contribution of that substance and can thus be compared with a reference substance, such as CO_2. Methane (CH_4), for example, is said to have a 28-fold higher greenhouse effect than CO_2 based on a period of 100 years (Myhre, 2013, p. 731). One kilogram emitted CH_4 therefore equivalents to 28 kilograms of CO_2. In this way, all greenhouse gases can be converted into in

CO_2 equivalents (CO_{2eq}) and summarized in the impact indicator "global warming potential" (GWP100).

Weighting is the most subjective part of the lifecycle analysis. Since impact categories are compared and certain aspects can be emphasized by the researcher with varying importance, it is possible to stress or downplay certain effects. Thus, especially in the case of comparative LCAs, preference can be given to positive or particularly negative ones. ISO 14040 therefore requires transparent documentation in the selection of the weightings, which serves to fully understand the results of the LCA for the audience. In opposite to weighting, *normalization* is a type of analysis to lean how different impact categories relate to reference values. In SimaPro, characterization and weighting are two standard predefined types of analysis that can easily be chosen by the researcher. The life cycle assessment is not only applied to assess environmental impacts of current products, but also to learn about potential impacts of new materials in pre-feasibility projects at the earliest stages of product development. Results from LCAs are used at decision making levels and in the assessment of material choices.

2.1.4. Interpretation phase

The impact assessment phase of LCA is aimed at evaluating the significance of potential environmental impacts using the LCI results. In general, this process involves associating inventory data with specific environmental impact categories and category indicators, thereby attempting to understand these impacts. The LCIA phase also provides information for the life cycle interpretation phase.

As stated in the ISO 14040 standard, the impact assessment may include the iterative process of reviewing the goal and scope of the LCA study to determine if the objectives of the study have been met, or to modify the goal and scope if the assessment indicates that they cannot be achieved. This is followed by a consistency, completeness and sensitivity analysis.

Issues regarding the choice and the evaluation of impact categories can introduce subjectivity into the LCIA phase. Therefore, transparency is critical to the impact assessment to ensure that assumptions are clearly described and reported. The interpretation phase can also be seen as an intermediate step between impact assessment and the issue of recommendations for action, since it is in the hands of the practitioner to present the results from the interpretation phase in an understandable and comprehensible manner.

Units such as CO_2 equivalents, MJ of required primary energy, or land and water footprint are expressed in common units, which are relatively easy to understand. More complex results, which are presented in Disability-Adjusted Life Years (DALY), Potential Disappeared Fraction of species per area and year ($\frac{PDF}{(m^2 \times yr)}$) or human toxicity in the equivalents of kg 1,4-dichlorobenzene (kg 1,4 DB_{eq}), can hardly be communicated. To guarantee the greatest possible intelligibility and to emphasize the importance of individual factors for an action recommendation, the results must be formulated according to the target group of the LCA.

2.2. Attributional LCA versus consequential LCA

As previously mentioned, LCA is used in a wide range of applications. The possible applications were mentioned in chapter 1. This includes the assessment of product- and service-related environmental impacts. LCA typically provides information about environmental impacts of the processes used to manufacture, consume, and dispose of a product. On the other hand, attributional LCA (A-LCA) does not consider effects arising from changes in the output of a product. In addition to that, A-LCA in most cases assumes average technology in the whole life cycle and provides information on direct environmental impacts of a product or service. By using normative cut-off rules and allocation to isolate the investigated product system from the rest of the system, A-LCA ignores a lot of the physical, ecological and economic causalities that are directly and indirectly related to the product. The calculation in A-LCAs is often a kind of stoichiometric relationship between inputs and outputs with the results depending heavily on the accuracy and precision of the provided data base (Brander et al., 2009, p. 2).

With the introduction of consequential LCA (C-LCA), practitioners move from the research question “which process is to blame for which environmental burden” to “what would happen if this process would be changed?” (Brander et al., 2009, p. 4). In contrast to A-LCA, C-LCA provides information about consequences of changes in the level of output (meaning: production, consumption and disposal) of a product, including effects both inside and outside the life cycle of a product. C-LCA models the causal relationships originating from the decision to change the output of the product, and therefore seeks to inform policy makers on the broader impacts of policies which are intended to change levels of production.

Another essential point is that while A-LCA uses average technology, C-LCA assumes state-of-the-art technology both in production and disposal. The following table 3 outlines the main differences between A- and C-LCA.

Table 3: Differences between A- and C-LCA (Brander et al., 2009, p. 4).

	Attributional LCA	Consequential LCA
Question the method aims to answer	What are the total product related impacts during the life cycle of a product?	What is the change in the total emissions in result of a marginal change in the production?
Application	Applicable for the assessment of emissions directly associated with the life cycle of a product. Not applicable for quantifying the change in total emissions resulting from policies that change the output of a certain product	Applicable for informing consumers and decision makers on the change in total emissions from purchasing or policy decision. Not applicable for consumption-based emissions accounting
System boundary	Process and material flows emerging from production, consumption and disposal of a given product	All processes and material flows which are directly or indirectly affected by a marginal change in the output of a product
Marginal or average data	Average data, average technology	Marginal data, best available technology
Market effects	Not considered	Considers market effects of production and consumption of a product
Allocation methods	Based on economic value, energy content, mass or material	Based on system expansion to quantify the effect of co-products on emissions
Uncertainty	Low to medium uncertainty based on the database. Relationships between inputs and outputs are generally proportional/ stoichiometric	Highly uncertain as it relies on models that seek to represent complex socio-economic systems including feedback loops and random elements

The concept of consequential LCA is not new, but was firstly mentioned by Weidema (1993). As of today, it has not yet been integrated into the ISO 14040 standard. In fact, the term attributional was not coined until 2001 (Curran, Mann, & Norris, 2001, p. 67), and was not defined before 2011 (UNEP/SETAC, 2011, p. 47). The 2006 revision of the ISO standard did not introduce the distinction between attributional and consequential LCA, but it was decided to separate the framework (ISO 14040) from the requirements and critical review (ISO 14044).

The fact that the C-LCA procedure is not separately standardized, with the implementation of A-LCA being already very complex, have not led to any appreciable distribution. While C-LCA is already well established in the agricultural sector (Thomassen et al., 2008, Dalgaard et al., 2008, Vázquez-Rowe et al., 2013, Tonini et al., 2012), it is still not common in the automotive sector. On the other hand, there are studies which only consider the partial production of vehicles or vehicle parts, but not a complete cradle-to-grave analysis (Stasinopoulos et al., 2012, Raugeia et al., 2014). The application of C-LCA however could be a useful tool for mobility planning, as it analyses the effects of changes in mobility strategy.

While the concept of consequential life cycle assessment has been presented here, it has not been pursued in this thesis for several reasons. Firstly, C-LCA merges the concept of A-LCA and economic modelling methods. As such and opposed to A-LCA, which accounts for immediate physical flows, it requires economic data to determine how physical flows can change because of an increase or decrease in demand for a given product (Mason Earles & Halog, 2011, p. 446). An essential prerequisite here would be the availability of market information for any product that shall be analysed in the life cycle assessment. This market information is usually implemented in C-LCA using models such as partial equilibrium models which allow to analyse possible effects of a policy on a market (Francois & Hall, 1997).

The following relationship is given by way of example. To produce the components used here, carbon fibre is necessary amongst other materials. The manufacture of carbon fibres and their resulting components is undertaken by suppliers who are using a market which is typically of a production capacity which roughly corresponds to the demand. If a manufacturer places a product on the market with a high number of units, production capacities will adjust to the increased demand. The global carbon fibre market was around 46.500 tonnes in 2013 with an annual growth rate of around 8 % and a production capacity of 104.600 tonnes (Holmes, 2014, pp. 38-39). In comparison to this, the global aluminium market in 2014 had a production volume of 54.000 kilotons with a growth rate of 7 % (Aluminium Leader, 2015), which shows that the market for carbon fibre produces a manageable amount. If a manufacturer changes its product design to using carbon fibre components, this can lead to a massive increase in the demand for such product, which must be met by the market offer. Therefore, production capacities may be expanded by additional factories, including all downstream processes such as polyacrylonitrile production, electricity, heat or transport which must be evaluated in terms of their contribution to further environmental impacts generated by a given material choice. Instead of asking “which process is responsible for which emission?”, C-LCA asks “what are the consequences of the increase of carbon fibre demand to such an extent that requires an increase of production, and how may this be satisfied?”.

This example represents a process that must be considered as additional information in the impact assessment in consequential life cycle assessments and shows the difficulty that is associated with C-LCAs. Furthermore, C-LCA assumes modern and competitive technology in unit processes, while A-LCA usually assumes average data for each unit process (Mason Earles & Halog, 2011, p. 445). Gathering this data and putting it in a model to analyse possible market changes is a very time intensive process, as it requires much research and great knowledge about the current market situation for the products of this particular life cycle assessment. For this reason, and the fact that the execution of an A-LCA is sufficient for the questions that Magna seeks answers to, C-LCA has not been pursued.

2.3. Methods

Two methods have been applied in this LCA which shall be presented prior to their application in the life cycle assessment. The CML impact assessment method has been developed by the Center of Environmental Science of the Leiden University in the Netherlands. In its current version of 2015 (3.03), it comprises eleven impact categories in its baseline version, and 50 impact categories in its extended non-baseline version and elaborates a midpoint approach. The baseline version is recommended for simplified LCA studies because it includes the common indicators used in most LCAs such as depletion of abiotic resources, climate change, human toxicity and photo-oxidant formation. In contrast to that, non-baseline indicators should be used in more detailed studies, as they draw a more detailed picture of major potential environmental impacts with different indicators calculated over different time horizons, e.g. global warming potential over 20, 100 and 500 years. This method is originally geographically limited to Europe, but normalization factors are available for the world as well (Huijbregts, et al., 2003). Three indicators of this method have been used in this LCA to assess the global warming potential (baseline), the resource depletion of fossil fuels (baseline) and the land competition (non-baseline). They will be explained further in the impact assessment in chapter 4.3.

Another method used in this LCA is the method by Berger and Finkbeiner (2014) to assess the total water consumption of products. This method is based on the on their 2014 publication (Berger, Finkbeiner, Van der Ent, Eisner, & Bach, 2014) and considered as a midpoint approach in water footprinting. It analyses the vulnerability of basins to freshwater depletion. A distinction between blue, grey and green water is made in water footprinting. The blue water footprint refers to the ground and surface water, which is evaporated directly during production. The green footprint describes the evapotranspiration of rainwater and is thus particularly important in agriculture (Hoekstra, 2009, p. 1965). The grey water footprint includes the amount of water contaminated by production processes and equals the volume of water required to dilute the used water until it reaches commonly agreed quality standards (Berger & Finkbeiner, 2010, p. 921).

This method analyses the vulnerability of basins to freshwater depletion. The result of this method is the water depletion index, which is based on the local blue water scarcity and denotes the risk that water consumption can lead to the depletion of freshwater resources. (Pré Consultants bv, 2016, p. 40). This method has been used to describe fresh water depletion that comes along with the manufacture of the automotive parts in this LCA. Impacts to water depletion will be presented in the impact assessment chapter 4.3.3.

2.4. Summary

Conducting an LCA is a complex task that is not excluded from human interests and preferences. The interpretation leaves a lot of leeway in the interpretation of the results, caused by the given possibilities of normalization and characterization in the impact analysis and interpretation phase. An LCA is more meaningful, the more adapted the system boundaries are set, and when individual processes have the highest possible level of detail. Through the interpretation and individual weighting, it may happen that LCAs, which have the same objects of investigation, lead to different results, due to the available data and assessment of environmental impacts. The impact assessment can be adapted to set the focus on certain aspects while simultaneously downplaying others. An LCA can thus be tailored in regards to the researcher’s goal or their client. As far as manipulation goes, LCA must follow strict scientific rules and guidelines to avoid the production of any desired result or bias, which is why it has been put into an ISO standard. To ensure transparency in the proper preparation of life cycle assessments, ISO 14044 stipulates rules in sections 5.1, 5.2 and 5.3 that must be observed when publishing LCA studies. These primarily include the extent of critical reviews by several independent and randomly selected auditors (DIN Deutsches Institut für Normung e.V., 2006, p. 58ff).

3. Assessment of existing studies in the automotive sector

The following section presents a selected catalogue of relevant studies in the automotive sector which deal explicitly with the application of lightweight hybrid components. They have been chosen as they pursue a variety of theses and objectives, which are described, examined, and evaluated for improvement approaches. The aim of this section is to present comparable studies, to present approaches and to identify problems and their solutions to derive the state-of-the-art in life cycle assessment as well as possible points of improvement.

The implementation of LCAs in the automotive sector is not a new approach to the assessment and evaluation of product-related environmental impacts. The preparation of life cycle assessments is used by many automotive manufacturers to illustrate progress in the manufacturing process with a focus on product care and evolutionary product development, to show development differences between vehicle series, and to show increasing environmental protection during production, use and end of life treatment.

It is up to the researcher to determine the scope of LCAs. Looking further at lightweight measures with a focus on glass fibre, carbon fibre and natural fibre reinforced plastics, it is striking that LCAs often compare concepts that do not ultimately find their way into actual high volume production. The LCAs in this area are also driven by OEMs or research projects as the literature research conducted by the author of this thesis has shown. Except for a few LCAs, the implementation of LCAs in the field of Tier 1 suppliers seems to play a rather insignificant role, with the most effective approaches to eco-friendly product development, production and end-of-life treatment through the eco-design approach. It could be assumed though that due to confidentiality reasons in the supplier industry, LCAs and their results are not published on supplier level.

The basis of this LCA is founded on a literature research concerned with up-to-date literature focussing on the production of LCA studies. Particular attention was paid to the thematic relevance to the automotive sector and to the materials under investigation. Further focal points were studies dealing with the topic of recycling lightweight construction materials in the automotive sector, as well as studies dealing with the development of life cycle assessments on the subject of carbon footprint, fossil fuel depletion, land use and water consumption. The temporal component was also important, so that recycling studies not older than four years were preferred, since it is assumed that major research and development efforts are being undertaken in this area. 48 studies have been screened in this process, with 16 studies focussing on LCAs in the automotive sector, 18 studies assessing environmental impacts of automotive lightweight components using LCA, and 8 studies comparing recycling scenarios of automotive applications and/or hybrid materials. The remaining 6 studies deal with methods for land use calculations and water footprinting. The following table 4 gives an overview about seven studies that shall be assessed in the upcoming chapters.

Table 4: Summary of selected research studies.

Title	Authors	Year	Description	Journal
A comparative life cycle assessment of a composite component for automotive	La Rosa et al.	2013	Cradle to grave LCA of interior side door panel made of hemp fibre and epoxy resin	Chemical Engineering Transactions
Environmental impact analysis of composite use in car manufacturing	Duflou et al.	2009	Comparative cradle to grave LCA of a steel BIW vs CFRP BIW	CIRP Annals - Manufacturing Technology
Simplified life cycle assessment of a hybrid car body part	Klocke et al.	2014	Cradle to grave LCA of steel/aluminium hybrid roof cross beam	Procedia CIRP
Life cycle assessment of carbon fiber-reinforced polymer composites	Sujit Das	2011	Comparative cradle to grave LCA of steel and carbon fibre composites	International Journal of Life Cycle Assessment
Recycling technologies for thermoset composites	Pickering et al.	2006	Technology overview of thermoset recycling technologies	Journal of Composites
Carbon fibre reinforced composite waste: an environmental assessment of recycling, energy recovery and landfilling	Witik et al.	2013	LCA of different end-of-life treatments for carbon fibre reinforced plastic	Journal of Composites
Water Footprinting: How to Address Water Use in Life Cycle Assessment?	Berger et al.	2010	Assessment of Water Footprints in LCA	Sustainability

As it can be seen in the table above, not all studies are conducted within the framework of an LCA. The studies by Watkin et al. and Pickering et al. address the problems of recycling carbon fibres and carbon fibre reinforced plastics. The focus lies on methods that enable complete recycling of fibres or methods that aim at the down cycling of long and aligned carbon fibres into short fibres with reduced material quality. Due to their high energy content caused by the PAN precursors and the downstream processing of carbon fibres, CFRP is ideally suited for recycling, but this also entails great difficulties (Witik et al., 2013, p. 89):

- CFRPs largely utilise cross-linked thermoset polymers for their matrices which cannot be re-melted or remoulded.
- CFRPs rarely consist of only CF and matrix as well as multiple different bonding agents and fillers.
- There is no standard composition for CFRP which leads to great variability between waste products.
- Identifying different compositions is technically challenging, making separation problematic.

These points have been thoroughly analysed in the studies conducted by Sujit Das, Witik et al. and Pickering et al., which are presented in the following chapters. In contrast to studies assessing impacts of automotive lightweight components, the study produced by Finkbeiner and Berger deals with the evaluation of the water footprint in life cycle analysis within the automotive sector. In the study, the approach to the calculation of water consumption is explained and applied based on the production, utilization and recycling of a VW Polo, a VW Golf as well as a VW Passat. This study will be presented later to clarify the problem of addressing water consumption in the scope of LCA.

3.3. Studies

Several selected studies will be presented in the upcoming chapters, summing up their focus and important results.

3.1.1. A. La Rosa et al. (2013) – A comparative life cycle assessment of a composite component for automotive

The researchers around A. De La Rosa from the University of Catania, Italy, conducted a life cycle analysis of an automotive interior side door panel. They state that “[...] the weight of the panel is a very important aspect for the impact evaluation because the vehicle use phase is dominant compared to the manufacture and end of life phase” (La Rosa et al., p. 1723). The presented study is a comparative life cycle study to compare the environmental impacts related to the production of a side door panel. The baseline material consists of a petroleum-based composite while the bio-based material consists of a hemp fibre using plant-based epoxy resin. The researchers assume that 50 % of the material is being recycled at the end of life and compare this scenario with the landfill scenario which is the common waste treatment scenario for composite materials and petroleum-based materials in this study. They conducted the study according to the ISO 14040 and ISO 14044 methodology using SimaPro 7.2 as modelling software, and applied the ReCiPe (H) impact assessment method.

The production of a composite panel made of plant-based epoxy resin and hemp fibre was defined as the functional unit for this LCA study. The group around A. La Rosa were able to collect data about the material flow including the resource extraction and further on the manufacturing phase, the material transport, the use phase and the end of life phase, presenting the origin of both the petroleum-based and the hemp-based material from their respective suppliers. By specifying the running capacity in the use phase with 200.000 km or 10 years respectively, they worked within usual assumptions within use phase scenarios (see other studies for comparison). Table 5 gives an overview about the investigated side panels.

Table 5: Specification of the investigated side panels (La Rosa et al. 2013, p. 1725).

Plant-based side panel (820 g)	Petroleum-based panel (1100 g)
Materials - Hemp mat (50 g) - SuperSap epoxy resin (430 g) *Scraps* - SuperSap epoxy resin (20 g) - Polyethylene (bag and pipe) (50 g) *Energy* - Electricity for vacuum infusion (900 kWh) - Hemp (lorry from England) - SuperSap epoxy-resin (lorry from Spain) *Waste Scenario:* - Recycling	*Materials* - Glass fibre (600 g) - Epoxy resin (500 g) *Scraps* - Composite (10 g) *Human labour (1,5 h)* *Energy* - Negligible for hand lay up *Transport* - Glass fibre (lorry from Germany) - Epoxy resin (lorry from Germany) *Waste scenario* - Landfill

In their study, the researchers not only compared different methods of production of the glass-fibres, but also the different methods of production of the resin. They used the ReCiPe Endpoint (H) V.106 as impact assessment method and came to several conclusions. In both scenarios, the transport of materials has already been considered. Concerning the glass-fibre production, it is noticeable that the production of conventional glass fibres scores worse in all categories than the production of hemp fibres. An exception here is the land use, which is caused due to the cropping of hemp. On the other hand, however, the researchers emphasize the positive impact of cultivation on arable soil and maintaining soil quality because hemp allows crop rotation. Furthermore, they indicate that a drawback of renewable materials often lies within the ecotoxicity and eutrophication. In this example, this is overcome by the fact that organic hemp is used which requires neither fertilizer nor pesticides. Furthermore, they indicate that the magnitude of the environmental impact varies depending on the distance between cultivation and the production site of the respective materials and products. For the production of one kilogram of hemp mat and one kilogram of glass fibres they provide the following environmental impacts:

Table 6: Potential environmental impacts associated to 1 kg of hemp mat and 1 kg of glass fibre production (La Rosa et al., 2013, p. 1725).

Impact category	Units	Glass fibre	Hemp mat
Abiotic depletion (ADP)	Kg Sb eq.	0,02	0,004
Acidification potential (AP	Kg SO2 eq.	0,017	0,0026
Eutrophication potential (EP)	Kg PO4 eq.	0,04	0,0006
Global warming potential (GWP)	Kg CO2 eq.	2,95	0,531
Ozone layer depletion potential (ODP)	Kg CFC11 eq.	2,49E-7	6,88E-08
Human toxicity potential (HTP)	Kg 1.4 DB eq.	9,52	0,136
Freshwater aquatic ecotoxicity potential	Kg 1.4 DB eq.	0,684	0,0571
Marine aquatic ecotoxicity potential	Kg 1.4 DB eq.	1,46E3	131
Terrestrial ecotoxicity potential	Kg 1.4 DB eq.	0,0412	0,00152
Land occupation	m2a	0,0692	1,54
Cumulative energy demand	MJ eq.	51,3	8,89

They emphasize that the epoxy resin attributable to the greatest effect. While the resin in fibreglass scenario produces around 67 % of the total impact, it is the hemp scenario approximately 86 %. The glass fibres contribute to around 28 %, while the hemp fibres by virtue of their characteristics as a renewable resource only to 7.2 % of the total load. The researchers decided to improve the environmental impact further takes petroleum-based epoxy resin bio-based epoxy resin to be used.

Table 7: Potential environmental impacts associated with the production of 1 t petroleum-based epoxy resin and 1 t plant-based SuperSap epoxy resin (La Rosa et al., 2013, p. 1727).

Impact category	Unit	Petroleum based epoxy resin	SuperSap epoxy resin
Abiotic depletion	Kg Sb eq.	59,4	0,01
Acidification potential	Kg SO2 eq.	40,3	25,44
Eutrophication potential	Kg PO4 eq.	6,6	6,9
Global warming potential	Kg CO2 eq.	6663	4079
Ozone layer depletion potential	Kg CFC11 eq.	1,26E-6	0,00
Human toxicity potential	Kg 1.4 DB eq.	490,44	545,17
Freshwater aquatic ecotoxicity potential	Kg 1.4 DB eq.	246,5	66,39
Terrestrial ecotoxicity potential	Kg 1.4 DB eq.	29,1	228,63
Cumulative energy demand	MJ eq.	2,16	1,90

The researchers emphasize the environmental friendliness of hemp fibres. As visible in table 7, the production of bio-based epoxy resin causes significantly fewer greenhouse gases, which are also related to lower energy and water requirements. The researchers state that the cultivation of hemp fibre is not in competition with the cultivation of food plants. As a final point, the researchers describe their end of life scenario, in which they assume that 50 % of the material goes to landfill, and another 50 % are going to be recycled. The recycling method stands out with a reduced overall impact (12 mPt), while the landfill is scores worse, because no material is made available in a second life (19 mPt). The researchers mention the problems that comes along with the end of life treatment of composite materials, however do not take into consideration a 100 % reuse strategy. The recycling strategy is further described as an incineration process, where the organic portion of the waste material serves as combustible. The rest of the material is fed to cement production, where it serves as a raw material. Unfortunately, the researchers eliminate the possibility for alternative EOL treatments in which the fibres would have been recovered, e.g. in chopping the material and downcycling them for use in new materials, such as composites in glass fibre reinforced polymers.

3.1.2. Duflou et al. (2009) – Environmental impact assessment of composite use in car manufacturing

The study by J. R. Duflou and colleagues from the Leuven University, Belgium, focusses the replacement of a body-in-white (BIW) made of steel by a BIW made entirely of carbon fibre reinforced plastics. A conventional BIW from a VW Lupo (model 1.4 A00) was used as a baseline vehicle, which prior to this study has been extensively used and analysed in the TECABS project, which stands for technologies for carbon fibre reinforced modular automotive body structures. The goal of this project was to find technologies and methods using carbon fibre composites to reduce a car's BIW weight using multifunctional parts and enhanced joining techniques (KU Leuven, 2004). The following table 8 summarizes the weight reductions that could be achieved.

Table 8: Summary of weight reductions and number of parts (Duflou et al., 2009, p. 10).

	Steel BIW	Target	CFRP BIW
Weight	203 kg	50 % = 102 kg	79 kg
Number of parts	200	30 % = 60	64
Static stiffness (max. rot. def.)	22,9 Nm/rad	22,9 Nm/rad	15,2 Nm/rad

The researchers derive from the EU directive proposal concerning the CO_2 reductions for light-duty vehicles that not only alternatives in propulsion and fuel types may lead to a decrease in emissions, but also that weight reduction is known to be an efficient way to reduce the energy demand of vehicles and the corresponding emissions during their lifetime. They state that "[…] in an effort to achieve a major weight reduction, the use of composites is currently intensively explored, with carbon fibre reinforced polymers (CFRPs) perceived as a promising alternative for steel and non-ferro structures." (Duflou et al., 2009, p. 9) This statement should be considered at a distance, since strength values, as achieved by the steel, can only be achieved with large-area CFRP applications. It is now more advantageous to use hybrid components made of metal and CFRP. The load-bearing metal component is reduced in the cross-section, while the CFRP is compensates for the loss of strength. Comparable studies by Klocke et al. (2013), Verpoest et al. (2005) and Taketa et al. (2006) also demonstrated the general feasibility of the integration or replacement of conventional materials by lightweight polymers.

In their comparative cradle-to-grave LCA, the team analysed the differences between the production process, the energy consumption during the use phase and the differences in the end of life treatment. Assuming a 200.000 km lifetime simulated using the standard of the motor vehicle emissions group (MVEG) standard urban drive cycle, a functional load 1,2 persons equating 71,2 kg per person and a 55 % filled fuel tank, the study excels at its level of detail describing the production process of the carbon fibres. The researchers describe the whole production process which is eventually reflected in the modelling phase using SimaPro 7 as software and the ecoinvent database as data library. The following Fig. 4 is a network overview in SimaPro displaying the production process of the carbon fibres and the composite material.

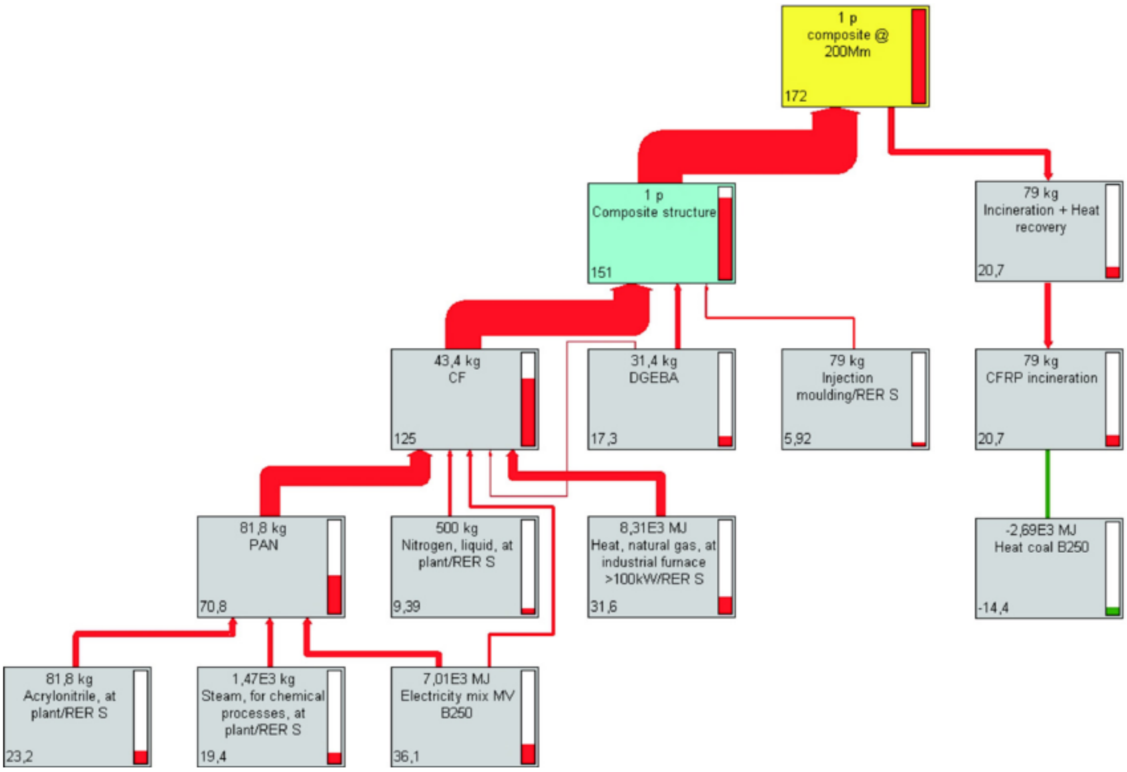

Fig. 4: LCA network overview for composite design variant (only flows representing at least 2 % of the total impact are shown) (Duflou et al., 2009, p. 11).

The research team points out that the major problem of CFRPs is still located within the end of life treatment, as an incineration is not acceptable given the fact that the EU ELV directive specifies a minimum reusable or recyclable fraction of at least 85 % on the complete vehicle level (The European Parliament, 2016). However, they do not mention the fact that the embodied energy in the CFRP will be lost to a considerable amount as the thermal energy gained by incineration reflects only a fraction of the energy associated with the production and transport of the CFRP. Duflou also lacks to mention complications regarding the repair-friendliness of CFRP compounds. It not safe to assume that CFRPs can be repaired as easy as metal or plastic automotive parts.

The team also highlights that economically feasible alternatives were hard to identify. They therefore decide to feed the CRFP residues to an incineration process at the end of life, but do not present an innovative end of life scenario. To calculate the thermal energy gained per kg of incinerated CFRP, they apply the Dulong-Petit-Law, which leads to an estimate of 34

MJ/kg. Assuming a 100 % incineration of the BIW, this amounts to 2686 MJ in the incineration process. In contrast to that the study does not list a total amount of energy used to produce and transport the material, which would have given an informative insight into the energetic cost/benefit ratio of the CFRP.

In the study, researchers pursue an interesting approach. They focus not only on the use of CFRP, but also on the associated consequences for the entire vehicle. When the reduction of vehicle weight reaches a certain threshold value through primary reductions, it can start a so-called weight spiral. This way, the automaker can redesign parts of the vehicle for reduced vehicle weight. In case of this study, the researchers show that the weight of the CFRP BIW is more than 130 kg below the baseline BIW. The researchers therefore took a step further and considered to use a smaller engine while retaining the driving dynamics. This resulted in secondary weight savings of an additional 31 kg by replacing the 1,4-l-petrol-engine with a 1.0-l-petrol-engine leading to a difference in fuel consumption of 0,76 l/100km. Additional considerations for changes in suspension and brakes were not persecuted, but are not indispensable in the course of lightweight spiral.

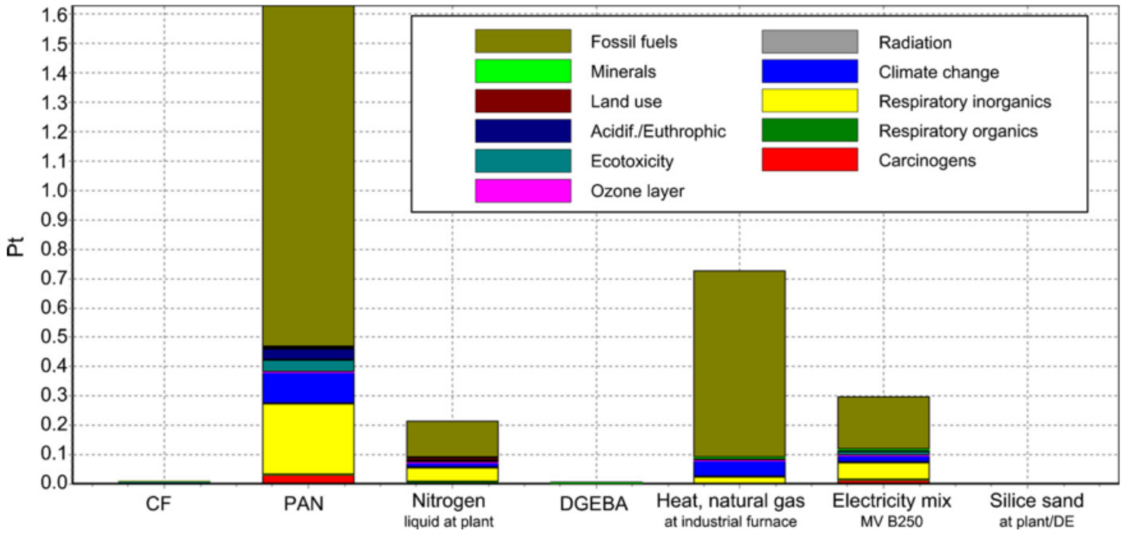

Fig. 5: Environmental impact associated with the production of 1 kg carbon fibres according to the Eco-Indicator 99 method (Duflou et al., 2009, p. 11).

Finally, the researchers applied the Eco-Indicator 99 methodology for assessing environmental impact. This method returns an aggregated point rating that is decreases or decreases proportional to the overall environmental impact. The overall effect for the composite BIW variant was determined with 172 Pt, of which 2.89 Ecopoints per kg were omitted in the production of carbon fibres and thus have the greatest single influence on the overall result. The impact of the polyacrylonitrile production becomes clear in the network overview in Fig. 4 and in the above Fig. 5.

Furthermore, "[…] the impact assessment demonstrates that the environmental effects caused by the EOL treatment of CFRPs through incineration with heat recycling (20.7 Pt for the full BIW) are an order of magnitude smaller than the production impact (151 Pt)" (Duflou et al., 2009, p. 12). Simultaneously, the team modelled the conventional BIW and came to an overall impact of 239 Pt, of which 196 Pt represent the fuel consumption due to the additional weight of 155 kg and the increased fuel consumption (5,6 vs 4,84 l/100 km). It is assumed that even though the impact caused by production and end of life treatment of the CFRP is about four times higher than the conventional BIWs impact (172 compared to 43), significant fuel savings can result in a break-even point between both design solutions after 132.000 km of use. Typical breakeven point analysis is shown in Figure 10 of the study by Witik et al.

3.1.3. Klocke et al. (2013) – Simplified life cycle assessment of a hybrid car body part

The research team around F. Klocke and colleagues produced a simplified comparative life cycle assessment of a vehicle's roof cross beam made of steel and aluminium die cast. In this study focussing on a body part, the research team compared a conventional steel made cross beam with a multi-material lightweight construction named VarioStruct. The analysed component combines a classic deep-drawn sheet metal absorbing the main load while a thin-walled light metal structure stabilized by ribs avoids buckling and bending under load. The two materials are form- and force-fit connected. The force-fit is achieved through cast aluminium riveting. The final connection of the two metal parts is achieved through "recasting around the edges of the component and shrinking of cast material during solidification" (Klocke et al., 2013, p. 485). The VarioStruct lightweight part was modelled in two variations, namely one using primary aluminium as base material, and the other one using secondary recycled aluminium.

Klocke et al. stated that even though "the handling of the entire manufacturing process is quite demanding, it results in several advantages" (Klocke et al., 2013, p. 485) The weight of the entire element could thus be reduced by 30 % compared to classical steel sheet designs and up to 10 % compared to a pure aluminium construction by optimizing the design and saving functionless material. Requirements regarding rigidity, crash performance and deformation characteristics were not negatively affected, but the redesign allowed for a greater integration of additional functions into the body part.

The study was conducted according to ISO 14040 standards and comprises resource extraction, manufacturing and assembly, use phase in the vehicle over 200000 km and end of life treatment. The data used in the life cycle inventory was widely available applicable from the manufacturer and using databases such as ProBas and GaBi 5. The impact categories were defined as the overall greenhouse gas emissions and primary energy depletion due to the fact that Klocke and his team only produced a simplified LCA. As for the use phase, the research team took average fuel consumption from manufacturer's information. This resulted in an average life span of 12 years and an average yearly driven distance of 13.600 km. Klocke et al. assumed fuel reduction values of $\frac{0{,}28\ l}{100\ km \times 100\ kg}$ for petrol engines and $\frac{0{,}35\ l}{100\ km \times 100\ kg}$ for diesel engines. This these fuel reduction values (FRV) are only applicable in cases where secondary weight reductions are considered. These include the redesign of important components such as the chassis, drive train, engine or brakes. Otherwise, the FRV for petrol and diesel engines are estimated with $\frac{0{,}15\ l}{100\ km \times 100\ kg}$ for petrol engines and $\frac{0{,}12\ l}{100\ km \times 100\ kg}$ for diesel engines (Krinke et al., 2010; Koffler & Rohde-Brandenburger, 2010). Efforts for maintenance and repairing have not been considered. The recycling scenario was modelled to reuse 95 % of the base material, leading to resolving geometrical bonds and remelting metal parts. The remaining 5 % were modelled to be taken into a disposal process.

The team concludes that the overall primary energy depletion as well as the greenhouse gas emissions depend mainly on the type of aluminium used for manufacturing and the type of fuel consumed in the vehicle. They point out that while the primary-aluminium based lightweight part does not differ much in terms of energy expenditures compared to the baseline part, the VarioStruct part using secondary aluminium has significantly lower environmental impact and is deemed to be eco-friendlier. Fig. 6 shows the different global warming potentials of the two lightweight scenarios.

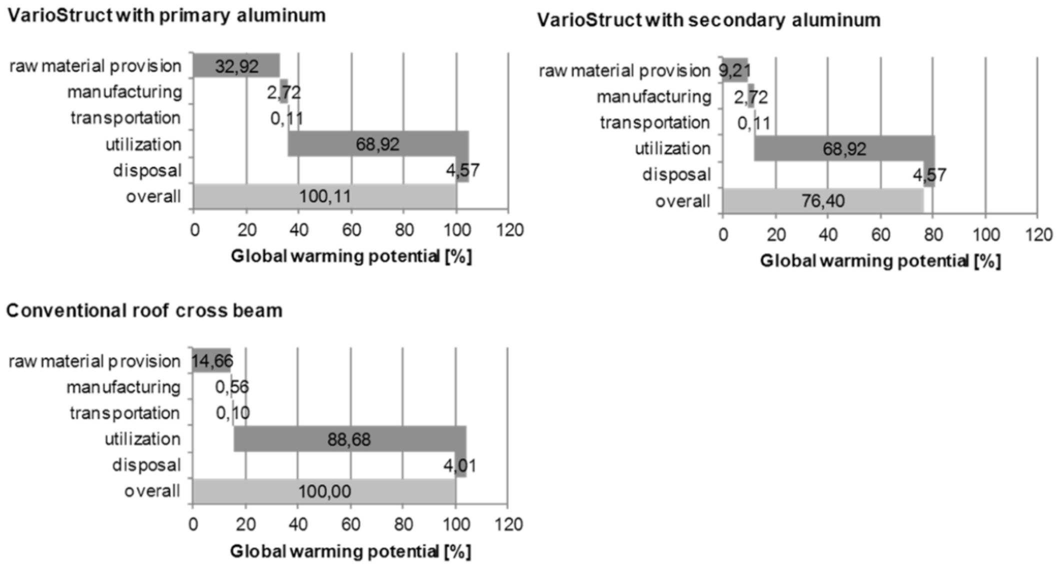

Fig. 6: Global warming potential of different cross beam variants (Klocke et al., 2013, p. 488).

It becomes clear that the two lightweight parts reduced the fuel consumption such that the global warming potential can be reduced by 20 % in the use phase. The researchers attribute this to the carbon dioxide-intense process for preparing the fuels.

A calculation to determine a breakeven point had also been done. The breakeven point for the diesel engine was found to be at 187.809 km, while the breakeven point for the petrol engine was calculated with 149.505 km for both lightweight scenarios. A major shortcoming of this study is the missing description of the recycling scenario. Klocke and his team state that 95 % of the material is being recycled and reused, however, they did not state which recycling technology they used in their model neither did they state which kind of technology was being assumed as basis for their model.

3.1.4. Sujit Das (2011) – Life cycle assessment of carbon fiber-reinforced polymer components

Sujit Das determined the life cycle benefits of two precursor types, two part manufacturing technologies and a fibre recycling technology. The researcher analysed the correlating impact of a 30,8-kg automotive steel flor pan as a baseline, and conducted a comparative LCA to compare these impacts to a combination of precursor types and manufacturing technologies. The author explains that in the course of increasing weight and increased consumption and emission values there is an interest in using innovative and lightweight materials. Above all, the use of lightweight materials in hybrid and electric vehicles is a driver in this development to compensate for the additional weight of the drive components in hybrid vehicles and the energy storage in electric vehicles.

Carbon fibre reinforced plastics have a great potential for weight reduction in vehicles, while at the same time meeting mechanical and processing requirements. Composite materials, which are up to 35 % lighter than aluminium and up to 60 % lighter than steel, can reduce the overall weight of the vehicle by up to 10 %. Disadvantages in the application of composite materials, on the other hand, are apparent in the complex production process, combined with high energy and material expenditure and the reusability of the materials. The main drawback, however, is the price, which is around 8 – 10 times higher than the steel price at about 25 – 30 $/kg (Das, 2011, p. 269).

The study was based on the US Department of Energy (DOE) Lightweighting Materials Section, which looks for low-cost, alternative precursors to conventional petroleum-based polyacrylonitrile to reduce the carbon fibre costs to 3 – 8 $/kg and thus create marketability in large-scale automotive applications. Within the study, two inexpensive alternative precursor materials are presented: textile-type acrylic fibbers and a renewable source material such as lignin. Programmable powdered preforming process (P4) and sheet moulding compound are presented as two competing cost-effective manufacturing technologies. The precursors are used with the production methods as four alternative scenarios and are compared in the LCA with the production of a floor plate made of steel. Table 9 shows the total of five scenarios.

Table 9: Manufacturing technology scenarios (Das, Sujit, 2011, p. 269).

Scenario	Description
Steel	Conventional stamped steel
PAN SMC	Textile-grad precursor to polyacrylonitrile (PAN) carbon fibre combined with SMC manufacturing
PAN P4	Textile-grade precursor to PAN carbon fibre combined with P4 manufacturing technology
Lignin SMC	Lignin precursor carbon fibre combined with SMC manufacturing
Lignin P4	Lignin precursor carbon fibre combined with P4 manufacturing technology

The cradle to grave assessment was done with SimaPro. The life cycle inventory data has been collected in collaboration with researchers and companies involved in the project. Database information was used in cases process and material data were not directly available to researchers. The functional unit was the floor pan for a large rear wheel drive vehicle such as the Cadillac CTS.

The study stands out for its comprehensive depth, especially in terms of details regarding individual materials, production processes and life cycles used in this study. Particularly noteworthy are the manufacturing technologies of the textile-grade carbon fibre precursor based on PAN and the alternative carbon fibber precursor based on lignin. The author uses a different approach to model use phase impacts of the vehicles by using the following equation:

$$Fp = L \times [FE_b \times (1 + Vwc \times FS_f)]^{-1} \times (\frac{Pm}{Vm}) \tag{1}$$

With:

Table 10: Components in the fuel reduction value equation (Das, Sujit, 2011, p. 276).

Fp	Life time fuel consumed by part [l]
L	Total driving distance [km]
FE_b	Fuel economy of baseline part [l/100km]
Vwc	Vehicle curb weight change du to FRPMC part substitution [kg]
FS_f	Vehicle curb weight vs. fuel economy improvement factor
Pm	Lightweight part weight [kg]
Vm	Lightweight vehicle curb weight [kg]

The most common method for modelling the life phase is presented in studies with the help of a calculation, which is determined by the reduced consumption of a vehicle by weight reduction caused by lightweight components. Together with the possible increase in the emissions required by the lightweight components due to their complex composition, a break-even point is determined, in which the fuel savings have compensated for the increase in production costs. The equation applied by Das determines the fuel consumption of the lightweight component over the use phase, which is compared with the basic component and is calculated for the initial vehicle consumption.

Das provides an interesting recycling scenario. Its first step follows conventional approaches, i.e. dismantling, shredding and separation of end-of-life materials similar to the steel scenario. But instead of adding the carbon fibre reinforced materials to an incineration process, the separation process is followed by a thermal treatment to isolate carbon fibres from their matrix material. This so-called pyrolytic recycling method developed by Jody et al. (2004)

necessitates part size reduction before the carbon fibre parts are fed to the thermal treatment. Das estimates the carbon fibre recovery yield to be around 98 %, stating that their results indicate carbon fibre properties comparable to virgin carbon fibres produced from PAN. In addition, the self-sufficient energy process can have a potential energy payback time of less than two years achieved through combustion of the polymer matrix without going further into detail.

Das goes into very deep detail in the results of the LCA study, but, unfortunately, only considers the primary energy requirements and CO_2 equivalent emissions as impact categories. Table 11 below shows the primary energy requirement as well as the emissions in CO_2 equivalent units. The production of the carbon fibres, independently of the starting material, is a very energy-intensive process which exceeds the production of the steel component many times over. The production of the lightweight component is not yet included.

The researcher points out that the production of the precursor (210 MJ/kg for PAN and 245 MJ/kg fibres for lignin fibres) accounts for about 30% of the total energy expenditure of the fibre production. The production of the actual components is also very energy-intensive, with the SMC method generally having a higher energy requirement compared to the P4 method. Conventional steel production is about 85 % less energy-intensive with 56 MJ per part. Analogous to the energy requirement, the CO_2 equivalents are presented. They are higher than in the steel scenario due to the elaborate materials and the embodied energy in the precursor. In addition, the energy expenditure and the emission load are higher for the PAN fibres based on fossil raw materials. Nevertheless, the difference is smaller than expected, since the energy content of the biomass of lignin fibres has been taken into account despite the higher efficiency in lignin-to-carbon fibre production.

Table 11: Life cycle primary energy requirements and GHG emission equivalents (Das, Sujit, 2011, p. 278).

Material/technology unit	Primary energy	CO_2 equivalent emissions
Per kg of material		
PAN carbon fibre	704 MJ/kg	31,9 kg/kg carbon fibre
Lignin carbon fibre	670 MJ/kg	24,2 kg/kg carbon fibre
Per kg of manufactured part		
PAN SMC part	345 MJ	16,9 kg
PAN P4 part	323 MJ	14,6 kg
Lignin SMC part	336 MJ	14,9 kg

Lignin P4 part	312 MJ	12.5 kg
Stamped steel part	56 MJ	4,4 kg
Life cycle of part		
Life cycle of PAN SMC	18.804 MJ	1.407 kg
Life cycle of PAN P4	18.232 MJ	1.347 kg
Life cycle of lignin SMC	18.800 MJ	1.400 kg
Life cycle of lignin P4	18.185 MJ	1.338 kg
Life cycle of stamped steel	18.308 MJ	1.478 kg

Using the life cycle modelling method stated before, Das lists the total primary energy amounts over the whole life cycle. This includes the material, manufacturing, use phase and end of life. The required life cycle energy amounts range between 18.185 MJ to 18.804 MJ per CFRP part compared to 18.308 MJ of the conventional steel part. The use phase as part of the total life cycle amounts for 93 % of the total impacts in the steel scenario, and for about 75 % of the total impacts in the CFRP scenarios. The difference is due to the higher energy requirements in the production of the carbon fibre precursors, the carbon fibres and the actual carbon fibre-reinforced polymer parts.

Using the recycling scenario stated earlier assuming a 97 % yield for carbon fibre recovery, the amounts of recovered energy range between 4096 MJ to 4294 MJ per PAN part and SMC part respectively. In the steel variant, this amount is calculated with 577 MJ, if about 95% of the steel can be re-used. Within the SMC-based technologies, "[…] higher SMC processing energy and more energy-intensive resin matrix material are not recovered at the recycle step and do not contribute to any life cycle energy use benefits" (Das, 2011, p. 279). The recovery process is thus not able to return the energy used in the production of the CFRP materials. It is also clear that lightweight construction alternatives are not capable of counterbalancing the bulk of the energy required during production during the life cycle and recycling process.

This means that the lightweight components cause the same environmental impact despite fuel savings. Only the greenhouse gas balance gives the CFRP parts a slight advantage of 1 – 10 %. Due to the financial burden that comes along with the production of the parts without appreciable consumption and emission advantages, there seems to be no advantage in using these materials in this scenario without value added to the vehicle properties. A different assessment method, e.g. according to CML, would have been very interesting in this study. The recycling of carbon fibres in the recycling process also offers an approach to improvement, with the author assuming that these can be recovered to 97% without greater fibre degradation. An exact consideration in the context of the recycling and recycling scenario is missing here, this being under the aspect of the embodied energy in carbon fibres and fibre-reinforced plastics.

3.1.5. S. Pickering et al. (2006) – Recycling technologies for thermoset composite materials – current status

Pickering and his team did not conduct an LCA but produced a study on different waste treatment technologies for composite materials. Instead they produced a study about different recycling technologies for thermoset composite materials. By pointing out the need to recycle these materials both in terms of limiting the use of finite resources and the need to manage waste disposal, Pickering underlines the difficulty in the recycling of composites given the fact that landfill is a relatively cheap alternative to recycling. Furthermore, economic incentives are less favourable for composite recycling, making a powerful legislation obligatory to encourage recycling to take place. Pickering and his team provide several recycling technologies, with mechanical recycling and thermal processes as the two main categories in treatment strategies. Fig. 7 shows the different approaches to recycling, either through mechanical technologies or using heat to separate matrix from fibres.

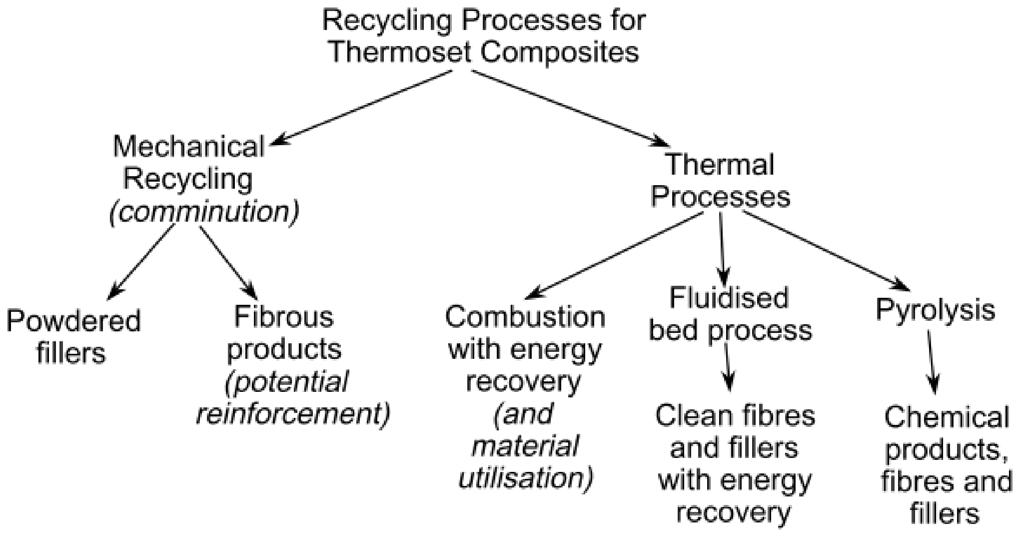

Fig. 7: Different recycling approaches according to Pickering (Pickering, 2006, p. 1207).

The methods provided in the study are suitable for both glass fibre and carbon fibre reinforced composites. It is stated that within the scope of mechanical recycling, most of the research has been done on glass fibre. The approach for mechanical fibre recycling is yet still applicable for carbon fibres, as the techniques are the same to a certain extent of the process. Typically, the recycling process involves a slow speed cutting process or a crushing mill to initially reduce material sizes to 50 – 100 mm, facilitating further processing and the removal of metal inserts. If the size reduction is done prior to transport, it assists in volume reduction and raises the overall efficiency of the recycling process. In a subsequential milling process, the material size is reduced to typically 10 mm and down to several micrometres followed by a classifying operation to separate the resulting fractions of different sizes. The remaining components can be used as fillers, substitutes for calcium carbonate in new SMC, or partially to replace short glass fibres in the production of virgin glass fibre under the premise that they are provided with longer fibres.

In terms of thermal processing, the research team focusses on the fluidised bed process and pyrolysis. The waste material is undergoing several steps in the fluidised bed process. First of all, it is going through a cutting process to reduce its size and fed into a fluidised bed of silica sand with a particle size of 0,85 mm. The sand is subsequently fluidised with hot air, reaching temperatures of 450 – 500 °C and fluidising velocities of 0,4 – 1 m/s. Polymers volatilise in the fluidised bed, releasing fibres and fillers which are then carried out of the bed as individual particles in the gas stream. After being separated in the gas stream, they can pass a combustion chamber where the polymer is fully oxidised. This oxidizing process can be used for the energy recovery to drive the whole process. As a result, the fibre product is in a fluffy form of 6 to 10 mm length and clean with little surface contamination.

While glass fibres suffer from a 50 % reduction in tensile strength depending very much on the temperature level used in the fluidised bed, carbon fibres show a lower strength reduction of only 20 % when processed at temperature levels below 550 °C. There are various opinions about the surface oxidation during heating in the oven, pending between no oxidation at all and a small reduction in surface oxygen contents. According to Pickering, the resulting short fibres can nevertheless be reused in bulk moulding compounds, non-woven veil or tissue products.

The team around Pickering concludes that if the recycling material is clean, of know origin and low contamination, the mechanical recycling process is the most suitable waste treatment for reinforced polymers. However, the powder being produced in mechanical recycling has only limited potential for reuse in the thermosets they originated from which is mainly owed to the lower mechanical properties.

Thermal processing finds its advantage in the ability to tolerate more contaminated inputs. It produces a very clean fibre product which yet cannot be compared to virgin fibres in terms of mechanical properties fibre length and possible char residues on the fibres themselves. This limits reuse applications but still produces useful organic products from the original polymer. Further research would have to be done to commercialize viable operation of these recycling technologies to lower cost of operation and to increase waste product quality to increase the value of the product.

3.1.6. R. Witik et al. (2013) – Carbon fibre reinforced composite waste – an assessment of recycling, energy recovery and landfilling

The research team around Robert Witik, Remy Tauscher and Véronique Michaud et al. from the École Polytechnique Fédérale in Lausanne, Switzerland, produced a study that assesses the environmental benefits of different end-of-life treatments for carbon fibre reinforced plastics. The team offers a small range of common but partly laboratory-scale recycling methods through pyrolysis, incineration with energy recovery and disposal via landfilling.

The researchers stress the increasingly difficult conditions for the treatment of waste in the automotive industry. The introduction of waste hierarchies, legal restrictions on the landfilling of hazardous and toxic waste and the EU's End-of-Life Directive, which requires 85% recycling of car scrap, makes landfilling of waste materials no longer a viable option. The researchers also mention the fact that CFRPs, as mentioned in previous studies, are energy-intensive materials that are ideal for recycling. Despite this, most of the recycling strategies are still within the stage of lab-scale methods, especially regarding the chemical recycling, microwave treatment, mechanical recovery and fluidised bed methods. Only pyrolysis has been developed to a stage that it could become a standard method in material recycling, which is why the researchers expect the greatest developments and results of this method. However, developments in the characterization of recyclates and restoration technologies, as well as methods for mechanical analysis, have to be advanced in order to raise them to the level of large-scale application with corresponding process reliability.

It is noted that the main drivers behind these research activities are environmentally related, with little research being done on the actual environmental benefits of recycling. An important point is the fact that by using pyrolysis as recovery technology, only 5 to 10 % of the initial amount of primary energy used in virgin carbon fibre production is necessary. But the researchers note that this argument is not very convincing, as the assessment of environmental performance does not only rely on the overall energy requirements in production and recycling. The overall benefits of recycling and recovering carbon fibres from waste must outweigh the total cost of manufacturing fresh carbon fibres and incineration. In other words, the sum of all environmental impacts of recycling must be lower than the production of virgin carbon fibres and landfilling of CFRP waste.

A major problem in the recycling of CFRPs is the fact that the mechanical, chemical or thermal treatment steps of CFRP wastes have a negative impact on the fibres, degrading the quality of the fibbers and their mechanical properties. In the context of a closed-loop strategy, this is disadvantageous since this prevents a theoretically infinite reuse of recycled material and makes the direct introduction into product systems as recycled carbon fibres (rCF) as a substitute for virgin carbon fibres (vCF) impossible. The researchers therefore speak of downcycling, since the rCF cannot meet the same requirements as vCF. Witik et al. used the LCA to compare the environmental impacts of 1 kg CFRP and to determine the differences between pyrolysis, landfilling and incineration with energy recovery. The researchers used SimaPro as modelling software and used the 2002+ impact assessment method to assess environmental impacts in the form of four rating categories. The lifecycle inventory data has been obtained from Ecoinvent 2.1 database. Six scenarios are considered in two cases, as illustrated in table 12.

Table 12: Waste treatment and recycling scenarios (Witik et al, 2013, p. 91).

Material replacement case 1: RCF replacing GF	Scenario 1: Landfilling of CFRP waste + New GF and resin production
	Scenario 2: Incineration of CFRP waste + New GF and resin production
	Scenario 3: Recycling of CFRP + resin production
Material replacement case 2: RCF replacing CF	Scenario 1: Landfilling of CFRP waste + New CF and resin production
	Scenario 2: Incineration of CFRP waste + New CF and resin production
	Scenario 3: Recycling of CFRP + Resin production

The results of the study were communicated in damage categories. Those comprise climate change, resources, ecosystem quality and human health. The impacts regarding the climate change category are expressed in kg of CO_2 equivalents ($CO_{2eq.}$). The resources category translates into non-renewable energy consumption and mineral extraction. This is expressed in MJ primary of non-renewable energy. Damage to the ecosystem has been portrayed as potentially disappeared fraction per m^2 per year ($\frac{PDF}{(m^2 \times yr)}$). An ecosystem quality score of $0{,}3\ \frac{PDF}{(m^2 \times yr)}$ implies a loss of 30 % of a species on 1 m^2 surface area per year. The human health indicator groups respiratory effects, ionising radiation, human toxicity and ozone layer depletion in one category which is measured in Disability Adjusted Life Years (DALY). A DALY score of 2 implies a loss of 2 years of life across the overall population.

In their study, the researchers come to very interesting results in the comparison of recycling strategies. In the first case, the researchers analysed the impact of different strategies under the boundary condition to replace GF with rCF. Using a landfill scenario as a baseline, the impact of incineration of end-of-life material was always lower than the impact of recycling. Fig. 8 shows the percentage impact compared to landfill, when recycled material is being used to replace glass fibre. While ecosystem scores were reduced by around 23 %, climate change, resource and human health impacts were increased by 95 %, 43 % and 119 % respectively. This is a very surprising result, as it qualifies alternatives to landfilling only as a non-preferably secondary option.

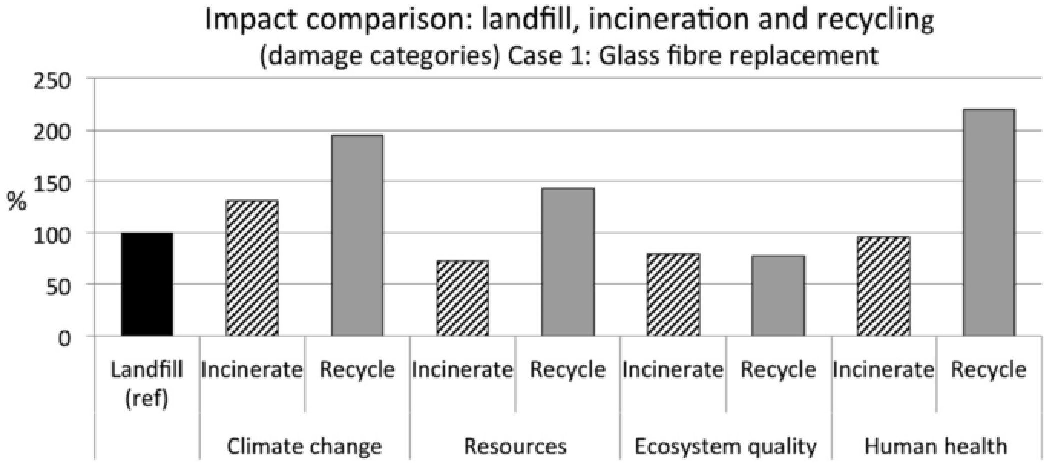

Fig. 8: Comparison of impacts from the recycling, incineration and landfilling scenarios, when recycled material is used to replace GF (Witik et al., 2013, p. 94).

Fig. 9 supports this conclusion as it shows that the kg CO_{2eq} values are significantly lower in the landfill baseline and the incineration and recycling alternatives. This is also a very interesting finding as it concludes both incineration and recycling in the case of glass fibre replacement not a viable option.

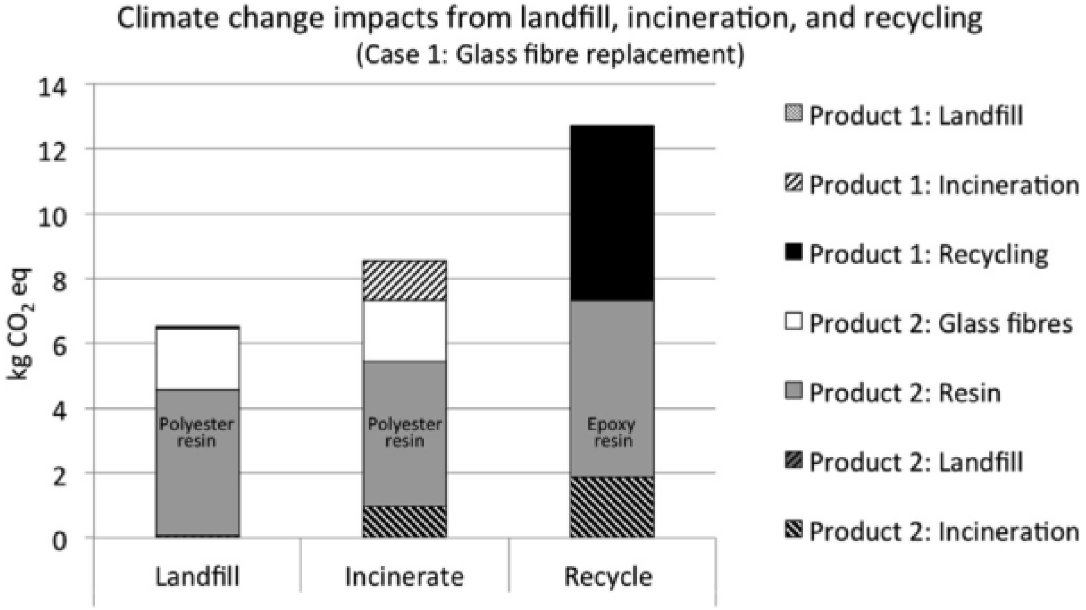

Fig. 9: Contributions to climate change emissions for the landfill, incineration and recycling scenarios for the GF replacement case (Witik et al., 2013, p. 95).

In the second case, the researchers assumed a scenario in which rCF are used to replace vCF. This scenario shows completely different results with recycling having the lowest overall impact, thus being a viable option in contrast to case 1. When RCF are used to replace VCF in an application, "[…] recycling shows clear environmental benefits, and this would therefore be the most environmentally favourable option for waste treatment" (Witik, Teuscher, Michaud, Ludwig, & Manson, 2013, p. 94). As the researchers point out in Fig. 10, impacts on the environment are significantly reduced in all categories when fibres are being recycled using pyrolysis.

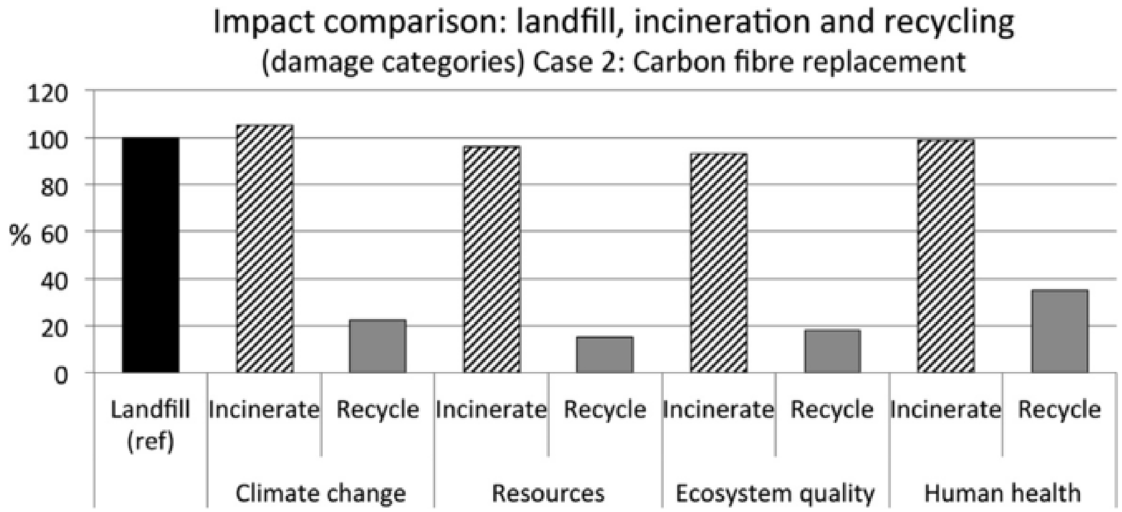

Fig. 10: Comparison of impacts from landfilling, incineration, and recycling for the CF replacement case (Witik et al., 2013, p. 95).

The reasons for the high landfill and climate change emissions lie in the high energy expenditure required to produce the virgin carbon fibres. The recycling scenario by pyrolysis is highly beneficial to the recycling of the material, prevents approximately 54 kg CO_{2eq} emissions and allows to absorb the emissions from the production of the material. In contrast to the landfill, approximately 45 kg of CO_{2eq} are abated.

Fig. 11 underlines the positive effects of carbon fibre recycling, making pyrolysis a suitable option for the end-of-life treatment of CFRP in case it replaces virgin carbon fibres in another application. Environmental benefits can only be seen in case recycled carbon fibres are used to avoid the production of virgin carbon fibres.

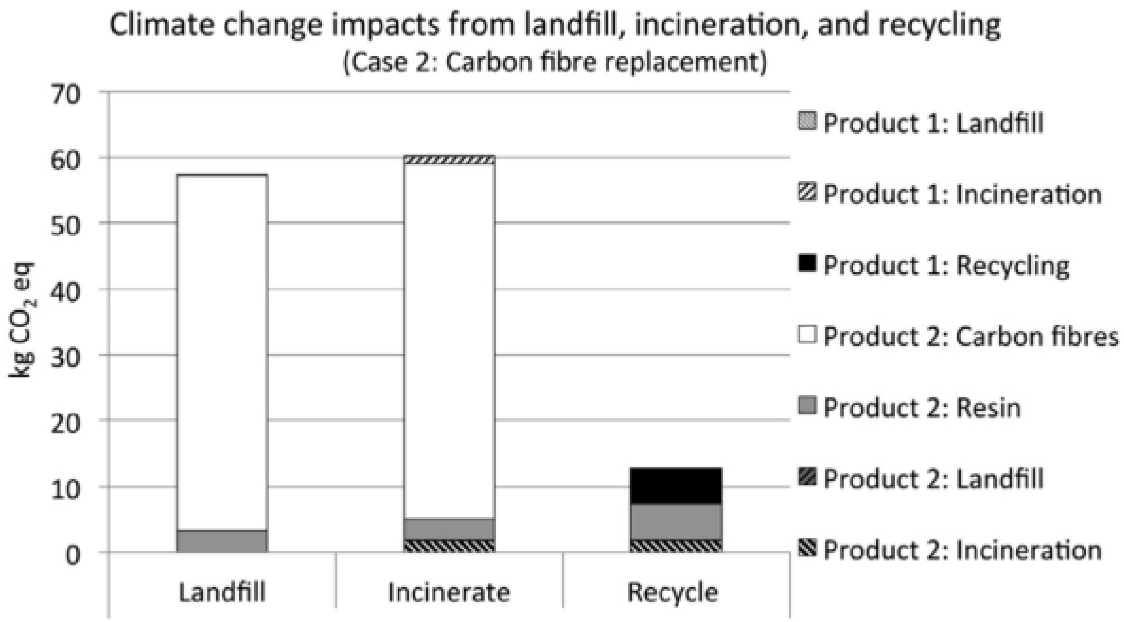

Fig. 11: Contributions to climate change emissions for the landfill, incineration and recycling scenarios for the CF replacement case (Witik et al., 2013, p. 95).

In their life cycle model, and also visible in Fig. 12, the researchers concluded that regarding CO_{2eq} emissions, the vCF-based CFRP part cannot reach a breakeven point within the 200.000 km assumed as vehicle lifetime. This is due to the high initial energy demand in the manufacturing phase of the vCF, accounting for almost 60 kg CO_{2eq} emissions compared to approximately 15 kg CO_{2eq} for the rCF and approximately 10 kg CO_{2eq} for the VGF before entering the use phase.

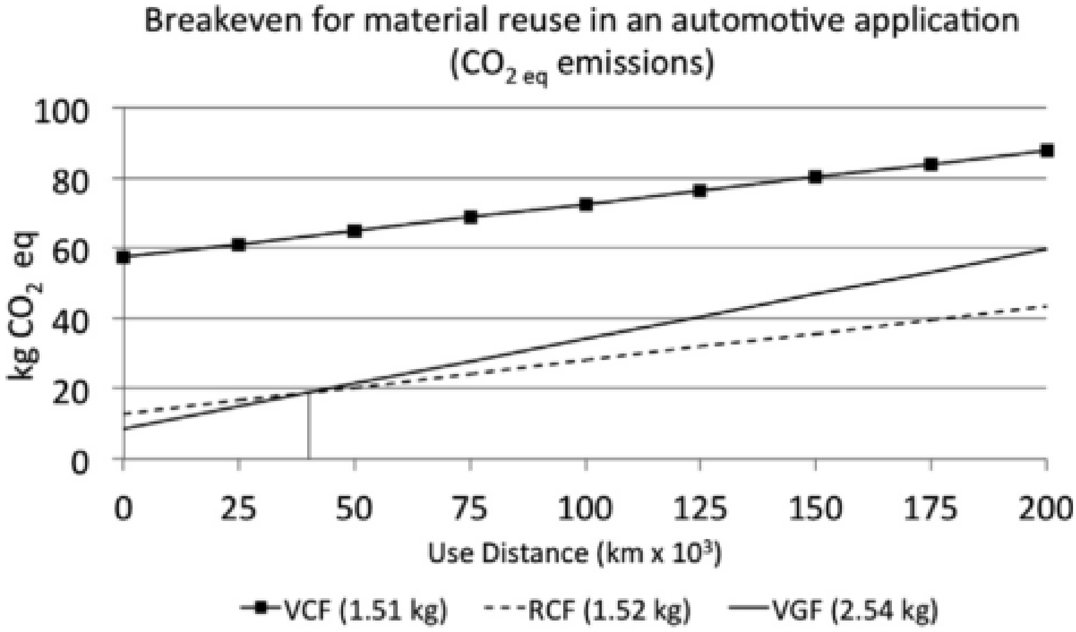

Fig. 12: Environmental breakeven analysis for CVF, RCF and VGF parts. Part weights are shown in brackets, life cycle distance is shown on the horizontal axis (Witik et al., 2013, p. 96).

3.1.7. M. Berger et al. (2012) – Water footprinting: How to address water use in life cycle assessment?

The research group around Markus Berger produced a life cycle analysis with the focus set on the water consumption during the life cycle of different vehicles. The size of the analysed vehicles ranges between a supermini car (2010 Volkswagen Polo 1,2 l TDI), a small family car (2010 Volkswagen Golf 1,6 l TDI) and a large family sedan (2010 Volkswagen Passat 2,0 l TDI). The study aims at assessing the fresh water consumption along the life cycles of different passenger cars. Fresh water consumption is defined as "[…] only the fraction of total water use that is not returned to the same river basin from which it was withdrawn due to evaporation, product integration, or discharge into other watersheds and seawater" (Berger et al., 2012, p. 4092).

The research team concludes that the production of a car consumes about 95 % of the total water consumption, mainly resulting from producing metals and polymers. Additionally, only 10 % of the water consumption takes place at the actual Volkswagen production site in Germany, while 90 % of the water consumption takes place in 43 countries world-wide. The team reveals that the impacts on health are dominated by water consumption in South Africa and Mozambique, which is due to the production of precious metals and aluminium. The main consequences regarding damages to ecosystems and resources are mainly caused by water consumption during material production in Europe. As a main result of the study, Berger et al. found out that the total life cycle water requirements range between 52 m^3 to 83 m^3 per car. Their study did not include individual washing as it highly depends on the "[…] individual use, personal attitude, and the technique applied, for which no reliable water consumption (evaporation) figures are available" (Berger et al., 2012, p. 4092). It is also assumed that the overall contribution of car washing to water evaporation is rather small, but should nevertheless be validated by future studies.

The research team had access to the Volkswagen internal slimLCI, which is an interface system enabling a consistent data collection and automated modelling of the LCI in the GaBi LCA software. The cradle-to-grave LCA study, conducted in accordance to the ISO 14040/ISO 14044 standards, modelled the vehicle life cycle including resource acquisition, manufacturing, use phase (150.000 km) and recycling according to Volkswagen's SiCon recycling process. They also included the crude oil production and the refinery of Diesel required in the use phase, using the New European Driving Cycle (NEDC) as basis for their use phase model (The European Parliament, 1998).

To approach the assessment of the water footprint, Berger et al. used a top-down approach, dividing the water consumption into shares consumed by each life cycle stage, assigning the water consumed to manufacturing steps and material groups, and finally allocating the water use to specific countries based on production mixes, location of suppliers and production sites.

In their impact assessment, the researchers were forced to apply multiple impact assessment methods, because there is no fully comprehensive method available covering all impacts. The following methods have been used in this study:

- The ecological scarcity method assessing water consumption based on physical water scarcity, measured in ecopoints/m^3,
- The impact assessment method of Motoshita et al. (2011), expressing the impact in Disability Adjusted Life Years (DALY),
- The method of Pfister et al. (2009) which includes five characterization models (freshwater deprivation, damage to human health, damage to ecosystem quality, damage to resources and overall damage) and aggregates the damages into a single-score result expressed in points/m^3.

The assessment uses watershed-specific characterization factors to specify impacts related to water consumption at Volkswagen's production sites. These were available from different sources such as the WaterGAP 2 model and Google Earth layers provided by the authors. They accomplished a significance analysis "[…] to identify the contributions of individual materials and manufacturing steps to the impact assessment and water consumption results of the production phase for the VW Golf" (Berger et al., 2012, p. 4094) They were able to point out the main causes for eutrophication (EP), ozone layer depletion (ODP), photochemical ozone creation (POCP), global warming (GWP), acidification (AP) and water consumption (WC), which is visible in Fig. 13.

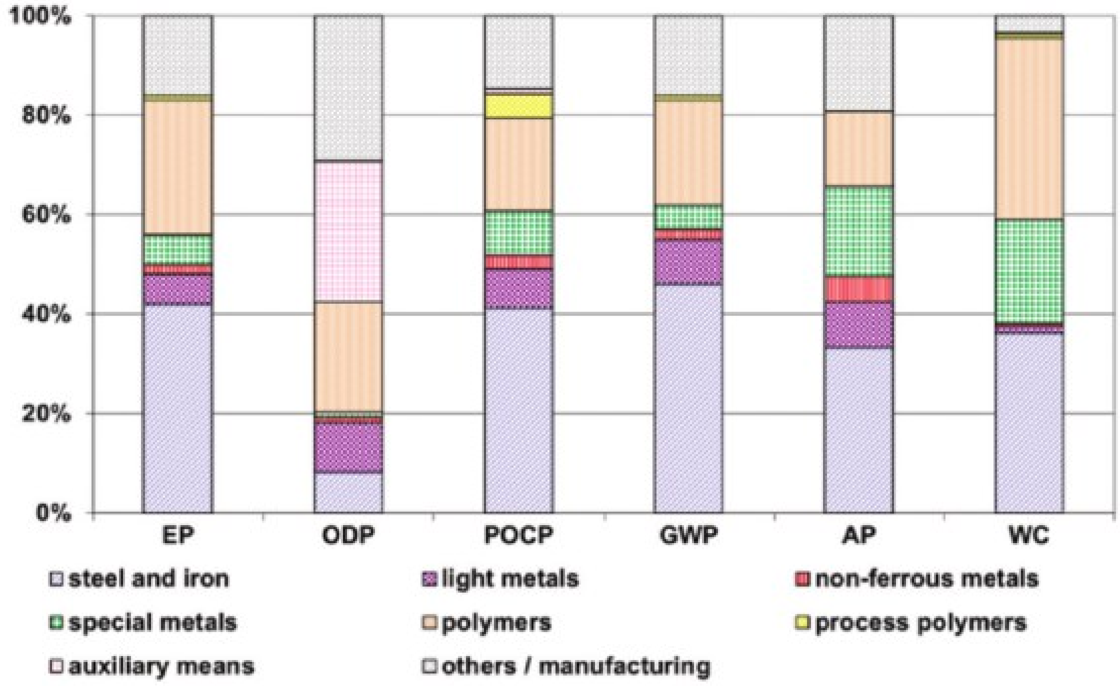

Fig. 13: Relative contribution of material groups to production impacts (Berger et al., p. 4095).

It becomes clear that the energy and water intensive production of metals and polymers dominate in almost all impact categories. The researchers assigned platinum metal groups (PGM) to the special metal category, which are used in the production of the vehicle to an amount of less than one kilogram. The high impacts of PGMs in the water consumption of around 20 % of the total impact is remarkable, as it shows what large material specific water consumption these materials can have. Using the impact assessment method according to Pfister et al. to assess the ecosystem damages during the production of the VW Golf, Berger et al. found out that damages caused by the depletion of resources only occur in countries where water withdrawal exceeds the renewability rate (water consumption to availability ration (WTA) > 1). This is interesting to know, because it means that just because a product requires a lot of water in the manufacturing does not mean it damages the environment.

The damage assessment relies largely on the consumption-to-availability ratio of water. This means also that a water intense vehicle manufacturing in watery countries, e.g. Austria or Norway does not have the same impact on the environment as the production in a rather dry country such as North Africa or California, USA. Furthermore, researchers found out using Motoshita's method that, due to high sanitation standards and a high degree of development, water consumption in countries like Spain or Australia does not cause damages to human health despite high physical scarcity in these countries. In summary, it is not sufficient to determine the water footprint without analysing the availability of water or the degree of development of the respective country. The information about how much water is being used during the production of a product or service is an interesting information, but the assessment lacks very important aspect if it does not consider the geographical, economic and ecological setting as well as the development stage a country finds itself in.

3.2. State of the art

The aforementioned studies differ in their implementation as well as in their results. Nevertheless, they have in common that the articles of investigation were modelled and described from cradle to grave. This is based on the ISO 14040, which is mainly based on the studies carried out in Europe. Although the studies that specify their geographic application in North America are not explicitly mentioned in ISO 14040, it can be seen that the studies are prepared according to a similar scheme. The use of SimaPro as a modelling software is widespread, and as such, automatically prescribes modelling under ISO 14040. In doing so, the largest possible life cycle inventory is created as a first step in order to then determine environmental impacts using different and precisely defined assessment methods. It is up to the researchers to use primary data, or to use information from databases or literature values from close studies and researches.

The models consist of one or several parts that are built using the available data. It is necessary to define system boundaries, goal and scope as well as the functional unit prior to modelling. The parts or systems that are to be assessed in the LCA should be as detailed as possible to gain as much information as possible. Not only the actual parts have to be created, but also means of transport, required amounts of energy, substances used in certain chemicals, life cycles and recycling scenarios should be created to represent every single substance, process and assembly within the comparison.

The assessment of studies has also shown that is quite common to iterate the system until requirements in terms of goal and scope definition have been met. Because the inventory in LCA contains several assumptions while the impact assessment depends greatly on regional or local aspects, practitioners often accomplish a sensitivity analysis. This is mainly done where data quality is not sufficiently reliable, especially in CF/CFRP production and their recycling respectively. By doing this, practitioners show the potential impact if, for example, energy requirements or process efficiency values are manipulated.

3.3. Variability of studies

Table 13 gives a short overview of the assessed studies within this LCA.

Table 13: Assessed studies in comparison.

Study	A la Rosa	Duflou	Klocke	Das	Pickering	Witik	Berger
Kind of study	Comparative	Comparative	Comparative	Comparative	Technology outlook	Comparative	Comparative
Real or ideal	Real	Real	Real	Ideal	n.a.	Ideal	Real
Country	Europe	Europe	Germany	North America	n.a.	EU	Germany
Reported units and impact categories	Impact assessment according to ReCiPe Endpoint (H)	Impact assessment according to Ecoindicator 99	Global Warming Potential, Energy Use	MJ Primary Energy, CO_{2eq} emissions according to GWP100	n.a.	2002+ CO_{2eq} DALY $\frac{PDF}{(m^2 \times a)}$ MJ primary energy	Multiple impact categories[1]
Full ISO LCA?	Yes	Yes[2]	Yes	Yes	n.a.	yes	yes

Recycling of CFRP in order to recover carbon fibres is a viable option if it replaces a virgin carbon fibre that would otherwise have to be produced. Witik et al. have shown that the recovery of carbon fibres is an energy-intensive process that requires additional energy sources to separate the fibres from their matrix. This can be achieved if the matrix material is used as a source of energy for the combustion process. On the other hand, with pyrolysis still

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[1] Impact assessment methods used in this study where mentioned as follows: ecological scarcity method, the impact assessment method according to Motoshita, the method of Pfister et al. comprising five different characterization models (freshwater deprivation, damage to human health, damage to ecosystem quality, damage to resources, overall damage).

[2] Even though not explicitely mentioned in the study, their LCA procedure follows the course of the ISO 14040 standard.

being a subject to further development, there are only few competitive alternatives with most studies assuming incineration with energy recovery as the only currently feasible option. Most of the studies have recognized the problem that comes along with landfilling of CFRPs and thus do not consider landfilling as an option, especially under the assumption that EU EOL and landfill directives tend to become stricter, allowing fewer and fewer materials to be dumped on landfills.

Many different results were presented in this assessment of existing studies, with varying depth of the studies. While Klocke et al. only produced a simplified LCA with global warming potential and energy requirement as indicators, Sujit Das and Pickering et al., as well as Berger et al. produced extensive studies with multiple impact categories and indicators to assess potential environmental impacts of automotive products. The team around Markus Berger produced one of only a few studies available in the automotive sector that assess the water consumption during a vehicle life cycle, and applied a variety of methods to not only determine the total amount of freshwater required during production, but also brought this water consumption into context. The total amount of required water is only of limited use if it is not brought into context, e.g. by a consumption-to-availability ratio in the respective country.

The different approaches used in the studies shall serve as an example of how life cycle assessments can be carried out. It is surprising that even though ISO 14040 provides several statements of requirements, studies can still be performed in great variety, leaving much room for the practitioner to put into execution the assessment following the individual needs and questions that need to be answered.

3.4. Areas for improvement

The studies above have been selected because they represent very detailed assessments of automotive products to date. There are a number other studies within the field of automotive applications, but the term “hybrid materials” often only relates to combinations of steel and aluminium, or aluminium replacing steel as material. The number of studies that engage in the topic of hybrid materials in the automotive sector is still within manageable amounts. Hybrid materials have only been introduced into the market with BMW being the only producer of vehicles having applications carbon fibre reinforced structures in the body.

More studies have to be conducted within this field parallel to the introduction of the materials, because they can show at very early stages in which direction the development will lead. This can be of great information, especially with the current research in recycling technologies that have the potential lift the myth of impossible carbon fibre recycling. The recycling technologies must however also find their way into industrial applications.
There are also a few points that should be mentioned here in terms of the execution of studies. It has not always been easy to understand the studies in terms of their scope. An accurate goal and scope definitions is essential before the actual assessment. Some studies have been very detailed in their definition of the functional unit, others only described the actual part as a functional unit instead of defining the production of a part including the fulfilment of all necessary functions as their functional unit. It is important to explain with great attention to detail the scope of the study.

Furthermore, it has not always been possible to determine to which extent processes had been modelled in the assessment. Some studies went into detail stating that only unit processes had been used, others integrated system processes in their models with very different results. The provision of production capacity can require a lot of energy and material, which is not respected if only unit processes are modelled. This here study will show that this needs to be defined and to be discussed, because processes, such as cataphoretic dip coating and painting require a great amount of energy. It can be said that 50 % of the expenditures in coating and painting are caused by the operation of a cataphoretic coating and paint shop (Schiffleitner, 2016).

The literature research also showed that the topic of uncertainty and sensitivity were treated inattentively. Many of the studies included sensitivity analysis in which the authors had changed certain parameters that obviously were considered as both influential and erratic. A thorough uncertainty analysis was only carried out in the very minority of studies. Practitioners of life cycle assessments should however pay more attention to the assessment of uncertainty in their studies. This is important especially if their research is focussing on new material combinations for which a broad informational basis is not yet at hand, because the significance of their results depends on the reliability of detailed process and product information. A state of the art life cycle assessment should always include a critical assessment of inventory data, which can be done by help of several means, such as Monte Carlo simulation, a pedigree matrix, or at least a sensitivity analysis.

A final point is that practitioners should communicate their results in an open and transparent manner. As already mentioned, LCAs can be tailored to reach a certain goal or to make a back a predefined statement. Transparency in weighting and characterization is necessary to guarantee an unbiasedness in the production of an LCA.

4. Comparative LCA of lightweight automotive hybrid materials

A vehicle's roof cross beam, cross member or joist, is an essential part of the body. This part can be found in the roof construction of most passenger vehicles. In addition to the shape stability of the vehicle, this serves, amongst other things, for crash stability during side and rear impacts. A further task within the scope of the functional integration is the inclusion of the hinges for the trunk lid.

The part usually consists of one or more several thin metal plates and is integrated in the vehicle by either welding, flange bonding, riveting or gluing. Main requirements of the part apart from those already mentioned are torsion stiffness and flexural stiffness as well as shear stiffness and modal requirements. It is also necessary to maintain the mechanical properties of the material under the influence of heat as the cataphoretic painting and corrosion protection requires temperature levels between 140 °C and 200 °C. The material selection for the cross member is shown in table 14. Numbers are based on prefeasibility calculations. Fig. 14 highlights one of four roof cross members in an automotive body part.

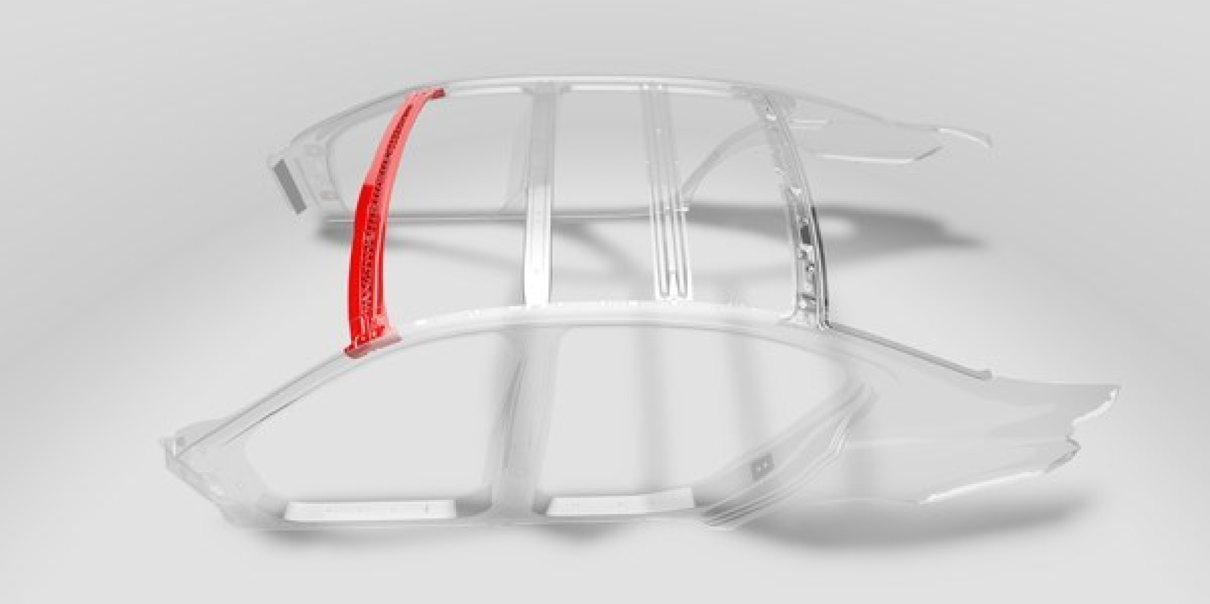

Fig. 14: Position of a roof cross member within an automotive body part (Exeon, 2016).

There are various reasons to replace conventional metal components with CFRP components. The most important reason weight savings that can be achieved with same component characteristics and component shape. Furthermore, it is possible to combine several functions and tasks in one component, i.e. in order by injection-moulding and producing parts directly in the mould.

Using this function integration approach, the number of components can be reduced, which can facilitate manufacturing and lower production costs. In contrast to that, CFRP alone is currently too expensive to serve as a single forming material, which is why automakers introduced hybrid materials that combine multiple advantages of different materials in one component. Aluminium for example is a very lightweight and flexible material, but simultaneously lacks important mechanical characteristics such as torsion stiffness or hardness when compared to steel. CFRP can counterbalance these disadvantages when applied to support possible weaknesses in the construction, but leads to higher efforts regarding bonding techniques, manufacturing and recycling.

At the very least, CFRP components are being increasingly used by vehicle manufacturers to put into motion the so-called lightweight construction spiral. The weight spiral is referred to as the process in which a number of components are reduced in terms of their weight. If a certain threshold of combined weight reductions is reached, other components be readjusted to the reduced weight. If, for example, a body in white can be reduced by 100 kg, the chassis, drivetrain and engine can be configured to reduce performance, but still maintain the vehicle's agility or driving dynamics. This is often referred to as secondary weight reductions.

BMW, for example, uses several hybrid material components in the vehicle body to build thin metal parts without losing the strength characteristics of the body. Fig. 15 shows the use of hybrid components named in such a BMW 7 body.

Fig. 15: Application of CFRP/aluminium hybrid materials in the BMW 7 hybrid b-pillar (CompositesWorld, 2015).

There are several requirements that need to be fulfilled by the material and to be handled safely during the production process:

- Required dimensional stability and mechanical properties of the body parts.
- Sharp and shrink-hole free CFRP edges to guarantee integration into the body.
- No penetration of sealing foil.
- No resin residues on aluminium to provide safe application of anticorrosive layer and painting.
- Exact position of CFRP in the aluminium sheet after pressing, cool down and shrinking.
- Wrinkle and blister free application of the holohedral bonding.

The materials used in this LCA study are shown in table 14 below. The benchmark will be a cross beam of sheet-rolled and die-casted aluminium with an initial weight of 7,01 kg. The first alternative is an all-SMC-manufactured CFRP hybrid component supporting a sheet-rolled aluminium panel. The second lightweight scenario is a CFRP laminate, which consists of several layers of so-called carbon fibre layup. The non-cured cut-away material in the CFRP laminate production is cut into chips of 10 to 50 mm and processed to a short-fibre SMC material. This way it can be used as material that otherwise would have been disposed of. This material has excellent features due to its high short fibre content and is ideally suited for use in the production of a supporting CFRP rib structure (Kaufmann & Goetzinger, LCA Interview II, 2016).

To assure functional integration, each variant accommodates two hinges for the trunk lid, adding a total of 1,6 kg to the construction. They are made of an aluminium sheet and weigh 0,8 kg each. The aluminium baseline part thus weighs 8,61 kg, with the lightweight alternatives weighing 7,04 kg and 7,27 kg respectively.

Table 14: Overview of different variants.

Material	Processing	Component weight	Weight reduction (%)
Aluminium	Sheet rolling, high-pressure die casting	7,01	Baseline
CF-SMC/Aluminium	Press moulding, sheet rolling	5,44 kg	22,4 %
CF-Laminate + Recycled CFRP+CF-SMC/Aluminium	Press moulding, Sheet rolling	5,67 kg	19,2 %
Trunk lid hinge	Sheet rolling	0,8 kg	n.a.

The following section discusses the production of the components and assemblies. In all three scenarios, an aluminium component is used as a cross member. The difference in lightweight construction is due to the reduction of the aluminium cross section and the addition of a reinforcing component made of carbon fibre reinforced plastic. Since two different aluminium materials are used in the baseline variant, two production lines exist to produce the part, in particular the production of rolled aluminium sheets and stampings as well as and aluminium high-pressure die-castings.

In the case of the lightweight construction variants, the components consist of different combinations of materials. While the first lightweight variant is using a CFRP part which is produced using the sheet moulding compound process, the second variant uses a CFRP laminate, which is produced using so-called layups. These layups consist of several layers of unidirectional carbon fibre reinforced layers, which are provided with a resin and bonded. The cut-off material from the laminate production is cut into small chips. For this purpose, a resin is added in order subsequently to produce so-called prepregs in a press, i.e. preimpregnated fibre-reinforced plastics which are neither crosslinked nor cured but remain completely elastic for a certain amount time.

These prepregs are brought into a corresponding raw form, a so-called preform, which is later applied to the aluminium component. These prepregs are transported from an Italian SMC manufacturer and Austrian laminate supplier to a Czech-based producer for automotive metal and hybrid parts. There, a press bonds the respective pre-heated semi-finished products to form a force-fit connection. The subassembly cooled down under predefined conditions and subsequently transported to the vehicle manufacturer where it is being integrated into the vehicle body. Additionally required parts can be installed for the functional integration before the vehicle leaves the assembly line and enters the cataphoretic dip coating.

There, a body pre-treatment is carried out in sequence, which consists of degreasing, phosphating and passivation for the application of a corrosion protection (Rosenau-Tornow, 2005, p. 89). In the following the cathodic dip coating is carried out with several drying steps after application of one lacquer layer. Above this, a filler is applied followed by the application of one or more basecoats and topcoats, which, in addition to the optical properties, also ensure the aforementioned requirements regarding durability against chemical and physical environmental influences. The application of a PVC underfloor protection, which is not relevant within this LCA and is outside the system limits, is also performed.

4.1. Goal and scope

The goal of this study is to compare different lightweight scenarios as depicted in table 14. The full aluminium part servers as a baseline, while there are two CFRP lightweight alternatives that are being compared to each other as well as to the aluminium baseline. The baseline scenario serves as benchmark in terms of environmental performance over a full cradle-to-grave life cycle. Using the assessment of lightweight alternatives, the goal is to determine the scenario with best environmental performance. The comparison is across the four main life cycle phases resource extraction (1), manufacturing (2), use phase (3) and end of life (4).

The functional unit of this study is the production of a roof cross member for structural integration into a premium-class passenger vehicle with an overall mileage of 200.000 km. The functional unit includes the fulfilment of following exigencies:

- Extraction of resources necessary for the required individual components.
- Manufacturing of the individual components and parts.

- All shipping and transport from and to the component manufacturers and to Magna Steyr Fahrzeugtechnik, Graz, Austria. Road transports have been modelled using EURO6 emission standards.
- Assembly of the automotive parts.
- Functional integration of the hinges for the trunk lid.
- Cataphoretically applied anticorrosion protection.

In order to create a more comprehensible picture of the production of lightweight body parts, it is necessary to approach the different life cycles step by step following ISO 14040. This study will not be followed by a critical review according to ISO 14044 as there is no need to as long as the study will not be published or presented to external organisations. Nevertheless, there will be a sensitivity study to show impacts caused by uncertainties in the modelling of the main processes. The required raw materials will be presented and analysed individually in chapter 4.2 The primary goal is to assess the environmental impact of the production of different lightweight body parts. A second goal is to compare the results of this LCA to results of previous studies to learn about the validity of the results.

While this study greatly emphasizes the use of primary material and process data where available, it has not always been possible to gather this data. There are various reasons for this, which can occur simultaneously. Manufacturers often do not have a complete picture of their manufacturing processes or input and output data considering environmental impacts under the credo of the LCA. While information on energy supplies, materials and process steps, cycle times, input and output as well as transportation distances are available virtually everywhere, waste streams and recycling processes are often not fully worked up. Manufacturers rely on downstream service providers for recycling. Even fewer data is quantified regarding emissions in air, water and soil, because of the fact that these emissions might not be measured technically for every single part production and manufacturing process.

Other suppliers do not wish to share critical process information as these details are the reason why these companies are ahead of their competition. In some cases, suppliers deliver a “black box” in which they share raw material amounts, energy requirements and/or waste materials, but in some cases, they do not wish share any information at all. At these points the exact mapping of production processes is difficult, even with the help of Ecoinvent data.

Nevertheless, data has been input from reliable sources and from SimaPro's database using European values whenever possible. The geographical limitation for this LCA is defined as Western Europe. While the model can be applied to other world regions, the data gained from this LCA may be incorrect or inappropriate for different regions of interest. Some substances[3] could neither be modelled nor found in the Ecoinvent database, yet they have been modelled in this LCA using dummy processes from the USLC database. This does not affect the geographical limitation, as the majority of datasets (86 out of 93) are based on European inventories. Other datasets have been taken from the European Reference Life Cycle Database (ELCD) or Industry Data 2.0 (ID). The intended audience is represented by product developers, product designers and engineers as well as researches within the field of LCA.

4.2. Inventory analysis

The inventory analysis describes the manufacture of the aluminium and carbon fibre materials as it has been modelled within SimaPro 8.2. The respective datasets have been appended in the annex. The processes this model is based on have been designed to take into account any kind of expenditures (heat, electricity) that are necessary to run a production site. SimaPro therefore allows the practitioner to decide between unit and system processes. The difference between those two is whether expenditures for machines, lighting or factories are considered in the calculation of the impact. This is a very important aspect since research has shown that the operation of an automotive paint shop accounts for about 20 % of the total primary energy consumption in the automotive production (Rosenau-Tornow, 2005, p. 105). There would be significant exclusions in the impact assessment if a process is only modelled as a unit process

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[3] This applies to the following dummy substances: zinc stearate (at plant/US), hydrogen peroxide (at plant/kg/RNA), silicon dioxide (at plant/kg/RNA), clear coat material, at plant/US, electrocoat resin, at plant/US, Pigment, at plant/kg/RNA, tinted clearcoat materials, at plant/US, inhibitors and additives used in CFRP production due to data being unavailable by the supplier(s).

instead of a system process. Production processes have been modelled as a system process whenever possible.

4.2.1. Aluminium sheet

For the manufacture of the aluminium sheet parts, a dataset was taken from the ecoinvent database using aluminium of Canadian production (CA-QC). Data regarding raw material acquisition as shown in Fig. 16 is already contained in the ecoinvent data. This Canadian smelter uses electricity from 96 % renewable energy sources (Aluminium Association of Canada, 2016). Alloying elements, such as manganese, silicon and magnesium are contained in the aluminium for mainly additional strength and anti-corrosion reasons. The production of the aluminium sheet up to the final component is following the production line as depicted below. Metal sheets are produced according to requirements by MAGNA Steyr by an Austrian aluminium material supplier. Aluminium sheets are then delivered to an eastern Styria based manufacturer for automotive parts forming the semi-finished products. From there on, the parts are delivered on the road to Magna Steyr, Graz, where they are assembled.

To follow the requirements stated by the functional unit at the beginning of the chapter, all parts necessary to fulfil functional integration have to be assembled as well, this comprises the assembly of the hinges for the trunk lid and is followed by the cataphoretic. The cut-off scrap is subject to uncertainty, but has been set to 50 % (Kaufmann & Goetzinger, LCA Interview I, 2016). This means that 1 kg material of an initial amount 2 kg are being cut off and treated as scrap after cutting, stamping, deep drawing, fine blanking or other downstream processes before the part is finished. The energy required during production amounts to around round 0,7 kWh of heat per kg of aluminium in the production, and another 1 kWh per kg aluminium is required in the processing step at the part manufacturer, using the respective national electricity mix of the country where production takes place (Goetzinger, 2016).

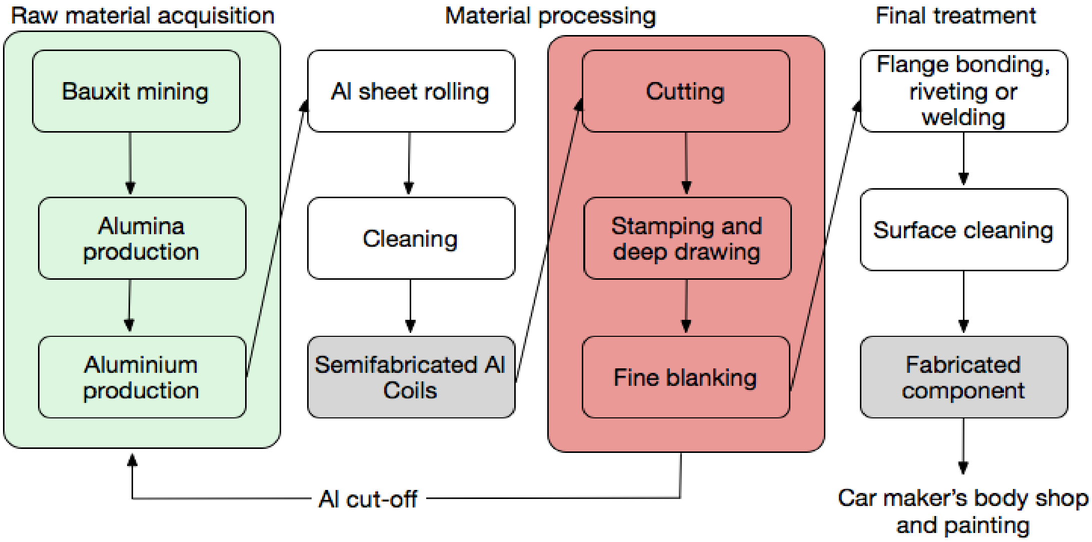

Fig. 16: Manufacture of a sheet-rolled component. Own work.

4.2.2. Aluminium casting

The production of an aluminium high-pressure die-casting part follows a the procedure as depicted in Fig. 17. The aluminium used in the process is derived from the ecoinvent database using primary aluminium of Canadian (CA-QC) production and is similar to the production of the aluminium sheet. The material is imported by the Austrian supplier and processed to a die-cast. The aluminium contains up to 5 % of aluminium scrap and up to 5 % of alloy materials and additives according to the ecoinvent dataset.

The Austrian supplier delivers the liquid aluminium to a downstream processor in Bavaria, Germany. After the part has been casted into its form at the Bavarian processor, it undergoes a heat treatment followed by straightening to achieve the coarse part tolerances. The total amount of cut-off material reaches about 50 % during the whole process chain (Kaufmann & Goetzinger, LCA Interview II, 2016). The part is being cleaned and degreased in an alkaline bath using the ecoinvent data (RER), assembled and delivered to Magna, Graz. From there on it follows the same downstream procedures including cataphoretic dip painting (application of anti-corrosive layer).

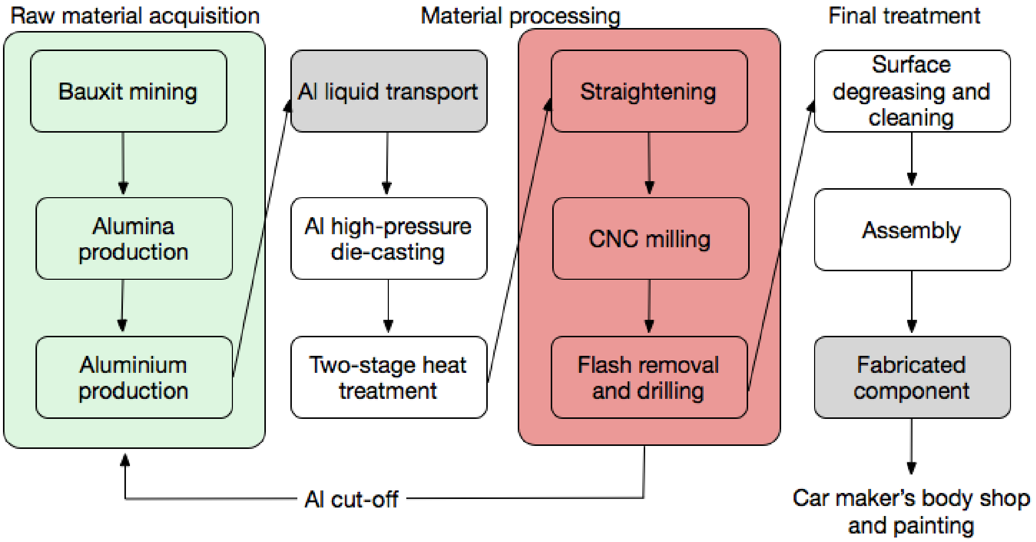

Fig. 17: Manufacture of a high-pressure die-casting component. Own work.

4.2.3. Carbon fibre and CF-SMC

The carbon fibre production was derived from a GaBi dataset and compared with literature values. A comparable dataset could not be found in the Ecoinvent. The basis of the carbon fibre consists of a precursor based on polyacrylonitrile. The fibre production is based on the usual three-stage industrial production (Pickering, 2006, pp. 272-273). Due to the high energy and raw material requirements as well as high production temperatures between 1700 °C and 2800 °C, the production of the fibres already entails great environmental effects.

The fibres follow several processing steps, namely washing and stretching, stabilizing at low temperatures (300 °C), followed by carbonizing of the fibres (1700 – 2800 °C) and surface treatment. This process has been explained by the US-based company Zoltek (Zoltek Carbon Fiber, 2016) and is conducted at the supplier in exactly this order according to the manufacturer.

An Italy-based manufacturer was chosen as supplier for carbon fibre sheet moulding components (CF-SMC) components. Fig. 18 shows the production of carbon fibres based on polyacrylonitrile (PAN). The PAN dataset was taken from ecoinvent, as well as all known inputs from technosphere. The required electricity and heat are also taken from ecoinvent. Because the production is assumed to take place in Italy, the national energy mix has been assumed in production. Emissions to air and water have been input in the dataset, while it is assumed that all waste materials can be reused resulting in virtually no waste materials.

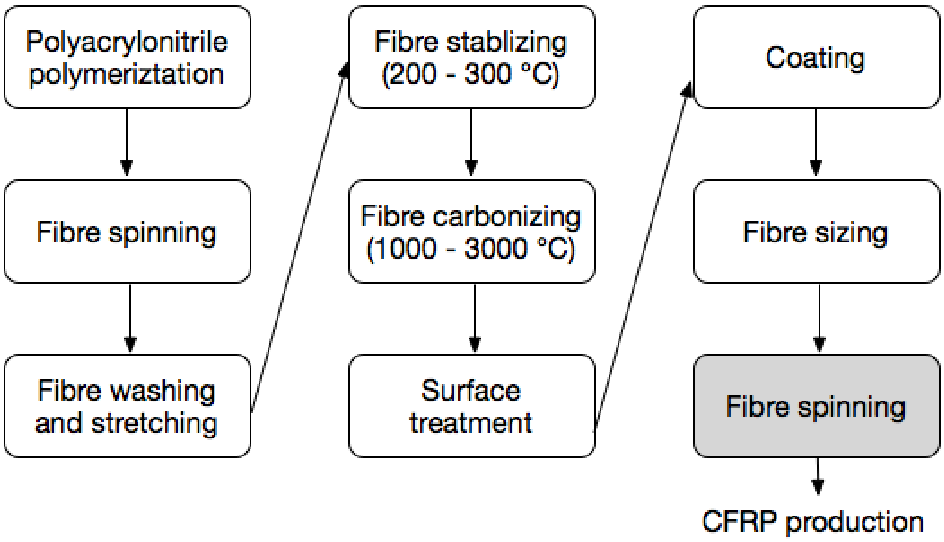

Fig. 18: Carbon fibre production. Own work.

The production of the SMC using the previously produced carbon fibres has been modelled based on the manufacturer's primary data and is carried out in several steps. The additives are first mixed in a paste and then processed. To produce 1000 kg SMC, about 100 kWh of electricity from Italian electricity mix are needed. According to the supplier, the entire production process produces approximately 5 kg of waste in the form of carbon fibres and 20 kg of hazardous waste are precipitated in the form of the paste, which has been modelled accordingly without recovery. The waste treatment has been defined as waste (hazardous material) for the paste and waste incineration of plastics (unspecified) for 5 kg of carbon fibres. The final CF-SMC is spun onto a bobbin from where it can be processed in another step.

The production of the carbon fibre prepregs and preforms is done at a manufacturing site in Austria. During the production of the preforms, about 50 % of the material is being cut off. But because the material has not cured yet, it can be reused in another process as depicted in the reuse scenario in Fig. 19. This leads to virtually no waste material in this process, but is should be mentioned that this can only be done once, because fibre length is reduced significantly in the reuse process, which therefore does not allow for a second reuse. The preforms are then stacked, packed and transported to a Czech-based company, where they are glued to the aluminium cross member. This process is shown in Fig. 19. The distance between the two manufacturing sites ranges between 950 – 1070 km, which is carried out with a 40-t-lorry fulfilling the at least EURO6 emission standard and which is 100 % loaded.

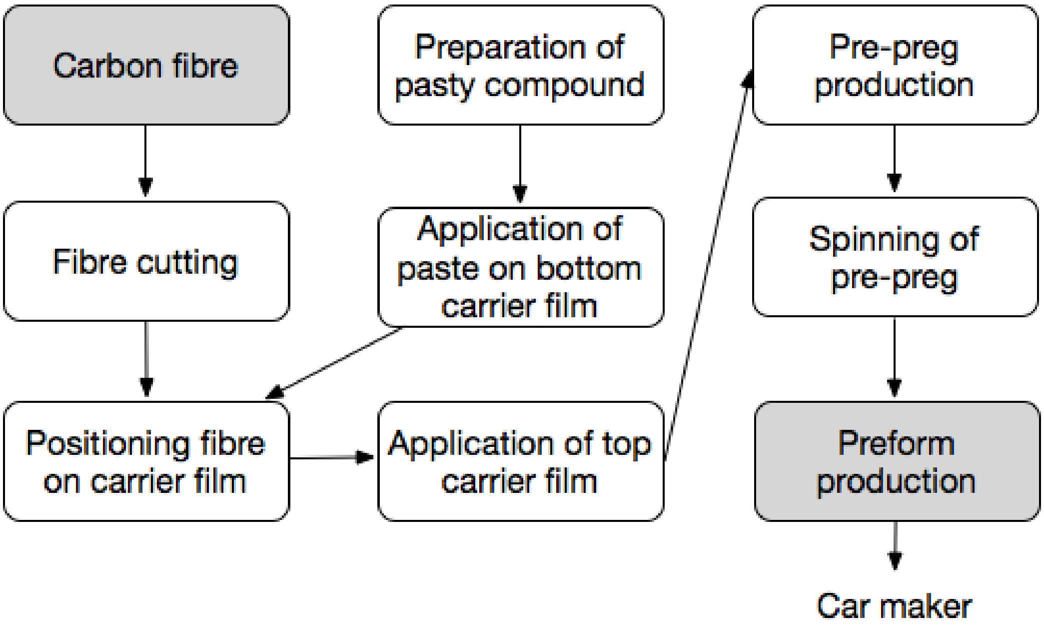

Fig. 19: Production sequence of SMC-prepreg and preform. Own work.

4.2.4. Carbon fibre laminate

The data set for laminate production is based on a literature value, which was confirmed by an in-house expert. The laminates are produced by layering a plurality of unidirectionally oriented carbon fibres with an epoxy resin as a matrix material. The individual layers are applied one above the other in a plant, each layer being adapted to the required laminate form by blending. To achieve the physical properties, the laminate must have an axis-symmetrical design. This is referred to as a balanced laminar structure. The prepreg laminate, produced by an Austrian supplier, is rolled onto a bobbin and transported to a Czech-based manufacturer to be assembled to in the hybrid body part. Here, similar to the SMC production, the transport is being carried out by a 40-t-lorry. The distance from the Austrian laminate supplier ranges between 370 – 410 km. The production process is shown in Fig. 20.

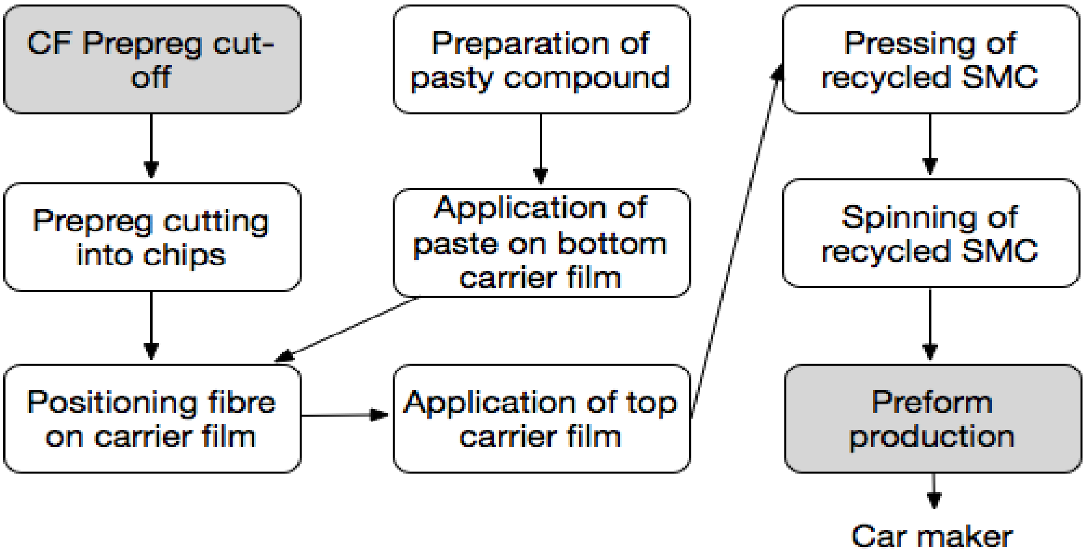

Fig. 20: Combined production of SMC-Pre-preg and preform in re-use scenario. Own work.

As previously mentioned, the hybrid body part in the second variant does not consist of a single type of CFRP, but is a combination of two types of virgin CFRP (laminate) and reused CFRP-chips (Nilakantan et al., 2016, pp. 4-6). The cut-off material in the laminate production, which was assumed to amount to about 50 % (Kaufmann & Goetzinger, LCA Interview III, 2016), is cut into chips of 10 – 50 mm of length forming a rectangular shape. It is then sprinkled onto a bottom carrier film. A resin can be applied to the film carrying the CF-SMC chips, but it is not necessary. They are subsequently covered by a top carrier film, pressed to a prepreg and spun up. While the cut-off-material in the laminate production is not modelled, the benefit which appears by using recycled laminate chips is accounted for by avoiding the production of 1.000 kg CFRP laminate in the production of recycled CF-SMC. This way, only the environmental impacts of the additional amount of resin are modelled in the recycled CF-SMC processing.

The recycled CF-SMC is assumed to consist of the same SMC produced by the Italian supplier. The resin has been modelled by using an ecoinvent data set based on Bisphenol A epoxy based vinyl ester resin of European production. This recycling process is assumed to require about 10 % of the initial energy to produce carbon fibre reinforced plastics, since all the materials are already in place and only need to be blended and formed into prepregs and preforms (Witik et al., 2013, p. 93).

Overall, this process cannot be referred to as classical recycling since the material properties are deteriorated compared to the original material. In other words, the material is not the same high quality as the original material before the internal recycling process. The correct designation would be downcycling, but this is not relevant in terms of the overall process, since the final product of the waste is a starting product of a downstream material production.

Cooling down to near-freeze temperatures as stated by (Nilakantan et al., 2016, p. 4) was not considered in the modelling because of missing data records, but should be modelled using this method and incorporated in an improved model. In the development of a series-based process, the improvement potential must be exploited and applied to guarantee process safety and product quality. The adhesive film required to bond the preform together with the aluminium body part is modelled using the composition stated in the material safety data sheet by the supplier.[4]

As a final step within the production, the application of a corrosion protection is carried out. In this step, the vehicle body passes through the cataphoretic dip coating for the application of the corrosion layer. The electrical conductivity of the car body is made use of in this process. While the aluminium baseline is completely cataphoretically coated, the lightweight components are only partially coated. The carbon fibre reinforced plastics are not sufficiently conductive to obtain a protective layer. Therefore, in the case of the lightweight construction alternatives, only the aluminium parts which are not covered by CFRP parts are coated. This is modelled in the LCA by the number of layers to be applied, which are multiplied by the component surface.

Due to the reduced conductivity, less corrosion layer adheres to the hybrid variants, resulting in a 73 % reduced surface area for application. Components that are not going to be visible in the final vehicle are usually not painted, which is why two layers are applied to the base component (anti-corrosive layer and filler). This results in total area of 5,08 m^2 being coated (two layers multiplied by 2,54 m^2 surface area). The lightweight construction alternatives are

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[4] L&L Products Material Safety Data Sheet for LF 501.

only partially coated. Of the total surface area of 3,56 m^2, only 0,99 m^2 can be coated due to the CFRP part.

4.2.5. Use phase modelling

The impacts of the utilization phase are usually determined by so-called fuel reduction values. This key figure is the central parameter that tells by how much fuel consumption of a vehicle is reduced by a lightweight construction. This value can be determined by the slope of the Willans-lines (Koffler & Rohde-Brandenburger, 2008). In previous studies, fuel reduction values of up to 0.5 l/100 km x 100 kg are assumed, which in the current state of knowledge is considered to be outdated. As described by Rohde-Brandenburger and Koffler, this value corresponds to 0.15 l/100 km x 100 kg for petrol engines, and 0.12 l/100 km x 100 kg for diesel engines. Insofar as secondary weight savings can be achieved by adaptations of other units (drive train, engine, brakes, chassis), the value can be increased to 0.35 l/100 km x 100 kg for petrol engines or 0.28 l/100 km x 100 kg for diesel engines. Koffler and Rohde-Brandenburger, as mentioned in their study, use the following formula, which is also used in this work to calculate the fuel reduction values:

$$\Delta C_{comp,i} = \left(m_{comp,i} - m_{comp,ref}\right) \times V_{100\,kg,NEDC} \times 0{,}01 \qquad (2)$$

With:

$\Delta C_{comp,i}$: weight induced fuel reduction value of vehicle component i [kg]
$m_{comp,i}$: part weight of vehicle component i [kg]
$m_{comp,ref}$: weight of referencial vehicle component [kg]
$V_{100\,kg,NEDC}$: fuel reduction value [l/100 km x 100 kg]

The overall impact during the use phase will be assessed in the impact assessment.

End of life (EOL) treatment and waste treatment scenarios

It is assumed that the plurality of all materials are recycled and made available for second life use during the EOL phase. It is also assumed that cut-off material during the aluminium production and manufacturing of the semi-manufactured products will immediately be recycled and used again, as the cut-off during the production phase is estimated to cause a 50 % loss of material which needs to be recycled.

For the aluminium baseline, it is assumed that about 95 % of the total end of life material can be introduced to a recycling process and reused, leading to significant decreases of the examined impact categories as chapter 4.3 will show.

As for the two lightweight cases, the assumption is made that the hybrid material combination can be separated and recycled analogue to the aluminium baseline. The CFRP materials will be fed to a thermal treatment to thermically decompose the matrix material and recover the raw carbon fibres. This process is known as pyrolysis as it has been described in the preceding chapters. There are two options for the practical implementation of the pyrolysis process:

- In a microwave oven with several hundred watts of electrical power in a batch process used in low-throughput applications.
- In a pyrolysis oven with power ratings of several kilowatts in a continuous process that should be considered on an industrial scale with high throughputs (Pimenta & Pinho, 2015, p. 380).

Unless temperatures reach values higher than 500 – 550 °C, there are a low to insignificant changes of the mechanical properties of carbon fibres. In case temperatures reach higher values, carbon fibres suffer from high oxidation and lose their mechanical properties, rendering unsuitable for a second life in applications in which they are applied especially because of their high strength (Pickering, 2006, p. 1212). Carbon fibres that are recovered using only microwave pyrolysis have shown to suffer from the microwave processing, which translates into lowered elastic modulus and ultimate tensile stress (Emmerich & Kuppinger, 2016). A batch oven was used to model this recycling strategy that does not show serious deterioration of material properties. It was decided that the pyrolysis using such an oven would be used to recover carbon fibres from scrap material. This setup has an electric rating of 15 kW (Manis et al., 2016; Linn High Term, 2016).

A thermal decomposition, usually co-incineration, as it has been the number one scenario in many studies, is not an option. Recent developments have shown that waste incineration plants refuse to accept waste products consisting of CFRP products because they lead to massive problems in the actual incineration plants, leading to excessive downtimes of the incineration sites. This is due to the fact that, in contrast to the common perception, CFRP components do not combust completely but tend to agglutinate and clump together. Furthermore, fine carbon fibres and carbon fibre dust leads to problems in electrical components in the incinerator (Mittelbayerische Zeitung, 2014; Limburg & Quicker, 2016, p. 139).

Another reason to consider the reuse of carbon fibres instead of combustion is the previously mentioned fact of the quantities of embodied energy within the fibres, resulting from the energy intensive production. Carbon fibres can also be woven into mats and textiles, which should be considered as second life application of fibres with diminished material properties (Pimenta & Pinho, 2015, p. 384).

Landfilling is also not a viable option mainly for three reasons:

- With the amount of CFRP products that are expected to be produced in the near future, there are simply not enough landfill sites available to accept the amounts of hazardous wastes.
- Landfilling is becoming increasingly more difficult, and it is expected that with exception of a few substances, landfilling will be completely prohibited in Europe.
- Heating value of CFRP lies above 6.000 kJ/kg with a total organic carbon content above 5 %, rendering it unsuitable for landfilling according to the European landfill directive.

4.3. Impact assessment

In this LCA, multiple impact assessment methods were chosen to assess life cycle impacts of the automotive components. The methods used here are:

- CML-IA baseline (V3.03) for the assessment of the Abiotic Depletion of fossil fuels (MJ) and the Global Warming Potential over a time horizon of 100 years (GWP_{100a}).

- CML-IA non-baseline (V3.02) for the assessment of the Land Competition (m^2a).
- Water footprint according to Berger et al. assessing the water use (Water Scarcity).

CML impact assessment is chosen because it covers the geographical scope of Europe. It is also the preferred impact assessment because it already contains indicators such as the global warming potential and the abiotic depletion of resources, which is defined as the depletion of fossil fuels and expressed in MJ. The extended, non-baseline CML impact assessment method is used to analyse the land competition caused by the production and recycling of the materials. Finally, the water footprint according to Berger et al. shall be applied here to learn about the consumption of freshwater throughout production and about possible benefits from the EOL phase. These methods have also been chosen because they are very up-to-date, dating back no longer than two years since the last update (2014).

4.3.1. Global warming potential

Global warming potential is expressed as the total sum of kg carbon dioxide emission equivalents [kg CO_{2eq}]. It can result in adverse effects upon ecosystem health, human health and material welfare. Climate change is related to emissions of greenhouse gases. The GWP_{100a} has been considered because it represents a key indicator in the assessment of the overall environmental performance of each material scenario. Fig. 21 depicts the global warming potential over a time horizon of 100 years of all three material variants. It shows the total global warming potential that is due to production broken down by each cause of the impact. The impact of the use phase is not shown in this figure.

As expected, the aluminium baseline has the lowest impact on global warming (108 kg CO_{2eq}) due to its lower overall energy use during production and processing. Both lightweight variants score higher, with variant A, using only sheet-moulded components in the production without reusing the CFRP scrap, scoring worse (217 kg CO_{2eq}) than variant B, where the CFRP scrap is reused (202 kg CO_{2eq}).

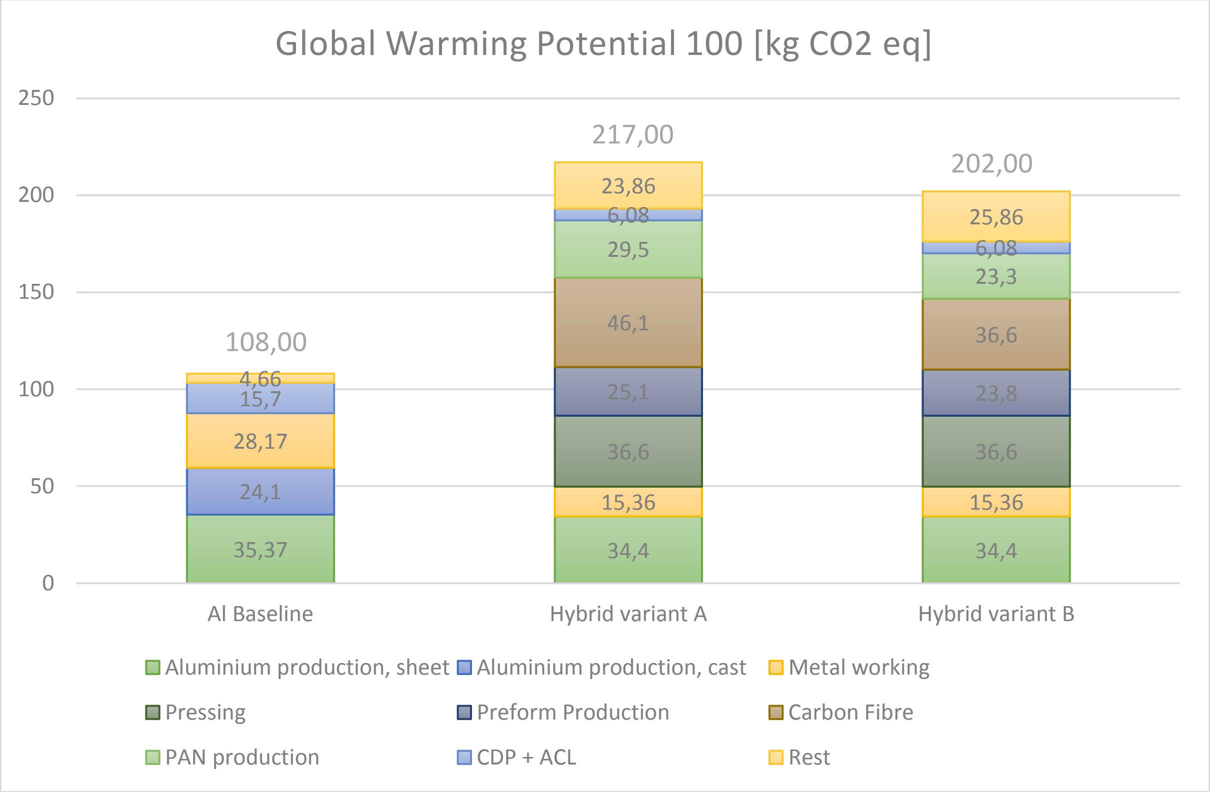

Fig. 21: Global warming potential 100a including NMVOC. Own work. Method used: CML-IA non-baseline 3.03.

Using the pyrolysis as effective end of life treatment for carbon fibre reinforced polymers allows not only to regain raw carbon fibres, but also leads to tangible reductions of the global warming potential. Aluminium recycling leads to a reduction of 114 kg CO_{2eq} in the baseline variant. This exceeds the initial impact caused during the production process by 6 kg CO_{2eq} and is due to how the model was made: it assumes that aluminium used in this scenario is produced in Canada, which causes relatively low emissions during production due to the use of renewable energies. At its end of life phase, it is recycled in Europe using an average European recycling process. This recycling process calculates recycling benefits based upon aluminium of European production, which entails higher environmental impacts during production and in return generates higher benefits from recycling in the end of life phase than Canadian aluminium.

The recovery of carbon fibres amounts to the minority of reductions in variant A (7,7 kg CO_{2eq}) and B (8,34 kg CO_{2eq}). Taking into account secondary reductions (e.g. energy from combustion of matrix material during pyrolysis) and the electricity required during the EOL process, reductions of global warming potential total to 114 kg CO_{2eq} for the baseline variant, and 79,4 kg CO_{2eq} and 79,9 kg CO_{2eq} for variant A and B respectively. Explicitly visible in Fig. 21 is the share of impact caused by the die-cast material, having an impact of 24,1 kg CO_{2eq} compared to 35,37 kg CO_{2eq} of the conventional sheet rolled aluminium. CDP + ACL represent the impact resulting from cataphoretic dip coating and application of an anti-corrosive layer. The impact is higher in the baseline variant because there is more area which can be coated in the aluminium version than in both lightweight versions.

4.3.2. Abiotic depletion of fossil fuels

This impact category indicator is related to the depletion fossil fuels due to inputs to the system (Pré Consultants bv, 2016, p. 4). The abiotic depletion is expressed in MJ for all variants as shown in Fig. 22 and related to the lower heating value. It has been chosen for two reasons:

- It is expressed in MJ of fossil resources required during the life cycle of all products. In contrast to the Cumulated Energy Demand, abiotic depletion of fossil fuels only takes into account fossil fuel depletion and disregards renewable energy sources. This paints a clearer picture of the actual resource requirement.
- The unit is expressed in MJ, which is identical to the unit in which the use phase impacts are expressed in, based on the fuel consumption of the vehicle. This eases communication of the results because impacts of the production phase, use phase and EOL phase can simply be summed up to one plausible number.

In the assessment of the depletion of fossil fuels it again becomes clearly visible that the aluminium baseline requires far less resources and thus energy during manufacture. It is important here to mention that the primary aluminium is produced in Quebec, Ontario, using electricity from hydro power plants, and then shipped to the Austrian and German part manufacturers. The expenditures for the production and processing of the aluminium parts predominate the overall impact of this indicator. The aluminium production and processing in the baseline variant requires 774 MJ, of which 262 MJ are owed to the production of die-casted part that must be kept at a certain temperature during production and transport. 509 MJ are required during production and processing of the aluminium part in both lightweight variants. The operation of the paint shop that is required to apply the anti-corrosive layer and

the painting requires around 213 MJ in the baseline variant and 83 MJ in both alternative variants. This is due to the fact that the baseline variant has a bigger surface area and two layers instead of one layer in the case of the hybrid variants.
The consumption of electricity has a significant impact in both lightweight variants, as it amounts to 1.105 MJ in variant A and 1.063 MJ in variant B. This is about 9 times as much electricity as in the baseline variant.

The production of the carbon fibre preforms claims most of the total fossil fuel depletion. Of the total fossil fuel depletion of 2.650 MJ in variant A, 586 MJ account for the production of the polyacrylonitrile, a further 614 MJ for the carbon fibre production and an additional 480 MJ are required to produce the preform. On the other hand, the total fossil fuel depletion in variant B amounts to only 2.480 MJ, of which 464 MJ are attributable to the production of polyacrylonitrile, 482 MJ are required in carbon fibre production, and 586 MJ are required for preform production. The rest of the depletion is owed to other processes, such as bonding, painting or metal processing.

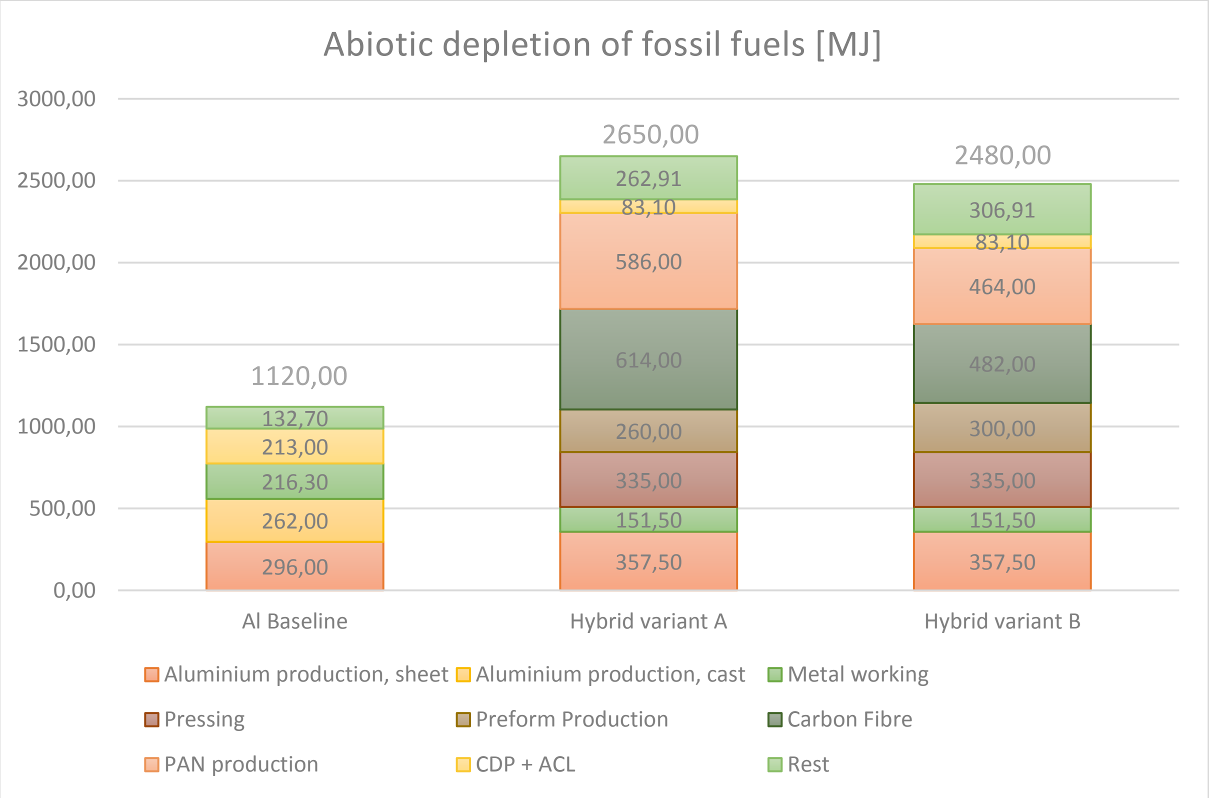

Fig. 22: Abiotic depletion. Own work. Used method: CML-IA baseline V3.02.

Including the EOL treatment with recovery of materials as already mentioned leads to a significant reduction of the abiotic depletion. It is assumed that around 90 % of the aluminium used in the parts can be recycled. Assuming that the aluminium will be reused in a second life, the indicator can be reduced by 1.003 MJ, amounting to 115 MJ after EOL treatment for the baseline part. This amounts roughly to the amount of energy required in the aluminium production. If this is transposed to both lightweight components, allowing to reuse the material, impacts can be reduced by 769 MJ to 1.881 MJ for variant A and by 778 MJ to 1.720 MJ for variant B. A reduction of 673 MJ is owed to the aluminium recycling in both variants due to the same amount of aluminium used in the hybrid cross beams (4,3 kg), and 121 MJ are owed to CFRP recycling in variant A, while CFRP recycling and recovery in variant B amounts to 131 MJ. An uncertainty analysis could be of great value here to clarify the importance of the aluminium production. This is done in chapter 5.1, in which the Canadian aluminium production is compared to an aluminium production of Asian origin.

4.3.3. Water footprint

Following the method description included in SimaPro 8.2, “The water footprint method according to Berger et al. analyses the vulnerability of basins to freshwater depletion. Based on local blue water scarcity, the water depletion index denotes the risk that water consumption can lead to depletion of freshwater resources” (Pré Consultants bv, 2016). Water scarcity is determined by the assessment of the water availability and the corresponding water consumption of each water basin. There are currently over 11.000 water basins modelled within the water depletion index (WDI).

Using Berger’s method, the amount of freshwater used in the production of all three variants can be determined. Fig. 23 shows the respective impact of each variant, with the overall footprint being the lowest in the aluminium baseline.

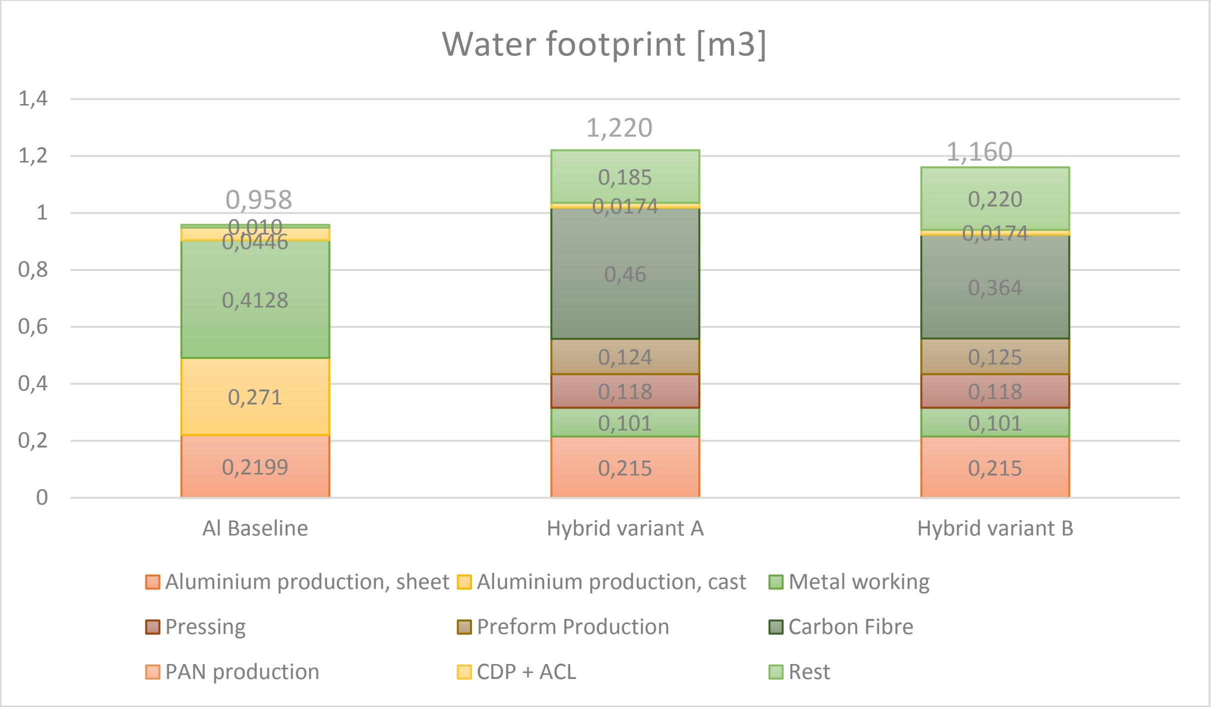

Fig. 23: Water footprint. Own work. Method used: Berger et al. (WDI) 2014, V1.00.

The water footprint is stated in m^3 and ranges between 0,958 m^3 for the baseline variant and 1,22 m^3 for the lightweight variant A. Due to the use of recycled fibres during the production process of the CFRP preform in variant B, the water footprint is slightly lower in this scenario with a footprint of 1,16 m^3. It can be said that, in the baseline variant, the production and processing of aluminium parts have the highest share of the total impact. Manufacture is responsible for a 0,904 m^3 share in the total footprint of the baseline, of which the die-casted component accounts for 0,271 m^3.

In contrast to that, only 0,215 m^3 water is consumed during the aluminium production and processing in both hybrid variants. The main impact in the lightweight scenarios is derived from the production of the carbon fibre (total of 0,460 m^3 variant A/ 0,364 m^3 variant B). The polyacrylonitrile is not the driving factor behind the water footprint, but nitrogen (0,169 m^3 / 0,134 m^3) and electricity (0,284 m^3 / 0,224 m^3) account for the greatest shares of the water footprint in the production of carbon fibres. So while the production of the carbon fibre has the highest impact in both lightweight, the impact of the cataphoretic dip and painting, where actual freshwater is used in the process, is negligible with an overall contribution of 0,0174 m^3 in both variants. If the impacts are broken down to their corresponding process, it becomes visible that electricity is the main reason for the water footprint in the lightweight variants. It is assumed that the water footprint is related to the production of the electricity (water use in the power plants as well as the water *consumption* of dams, required amount of cooling water in power plants, etc.) causes this impact. Expressed in numbers, the total share of electricity to the water footprint is calculated with 0,534 m^3 for variant A and 0,481 m^3 for variant B.

After recycling, the water footprint decreases by roughly 25 % in the baseline variant, and by 17 % and 16 % in the lightweight variants. It should be mentioned here that this does not mean water can be recovered, but more likely water can be saved by avoiding additional production of new material when recycled material is used.

4.3.4. Land competition

The land use indicator relates the changes in land use per square metre and year (m^2a). The model in SimaPro 8.2 applies the CML-IA non-baseline method. There is the option to use the Eco-Indicator 99 life cycle inventory assessment method to assess the land use, but in this method, the land use is being expressed in potential disappeared fraction of species per area and year, which does not give direct information about the actual land competition.

In the model, as visible in Fig. 24, it is again the aluminium baseline that leads to the lowest land competition values with 9,25 m^2a, and 7,95 m^2a after recycling has been taken into account. In contrast to that, land competition indicators double in the lightweight variants with 18,60 m^2a for variant A and 18,10 m^2a for variant B during manufacture.

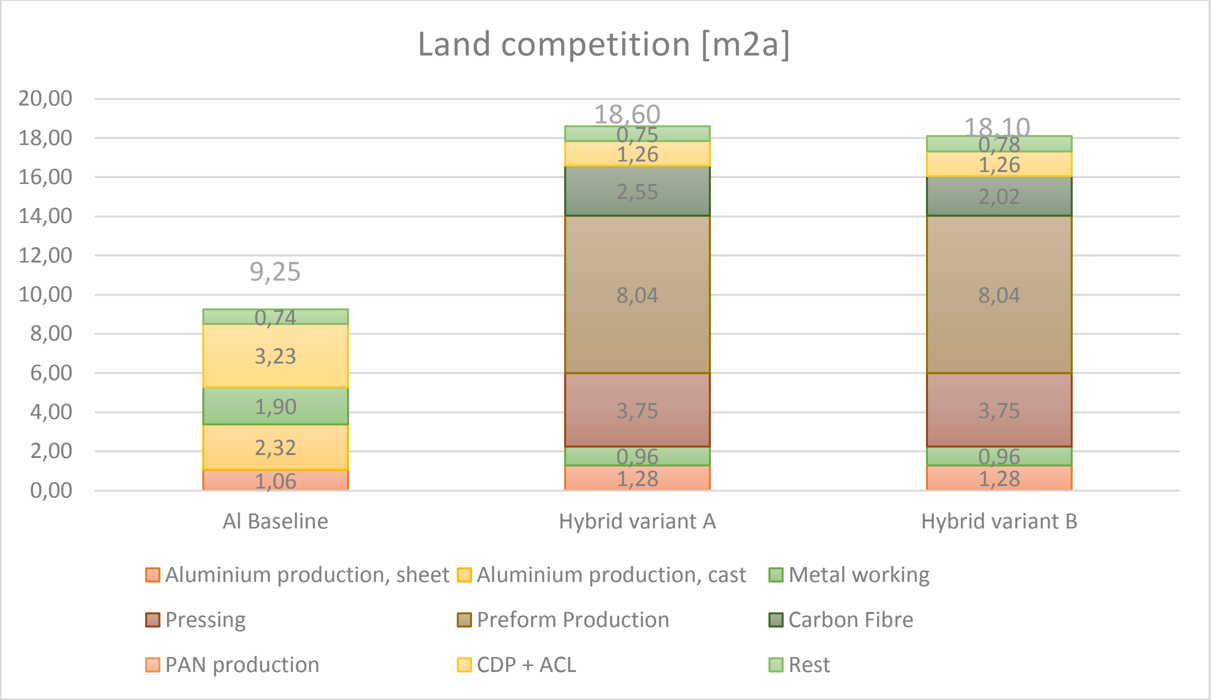

Fig. 24: Land competition. Own work. Method used: CML-IA non-baseline V3.03.

The land competition is dominated by the electricity necessary in the production and processing of all part. While, in the baseline variant, electricity amounts for 3,61 m^{2}a, the share of the total impact caused by electricity consumption is 15,96 m^{2}a in variant A and 15,51 m^{2}a in variant B. This can be interpreted as impacts related to the production of electricity, which increases land competition by mining activities. This also makes land areas simply unavailable for use, e.g. in case of dams, which use immense areas for electricity generation. Analogue to the water footprint, the decreasing values in the recycling phase should be understood as changes in land competition that can be avoided if materials are recycled. These amount to reductions of 1,3 m^{2}a in the baseline. The recycling scenario for both lightweight components requires 15 kWh per kg for the recovery of the carbon fibres. This leads to an additional burden of 10,1 m^{2}a in variant A, and 10,9 m^{2}a in variant B, because the recovery of the actual carbon fibres is not attributed with any benefits. This is not shown in the above figure. Aluminium recycling however leads to benefits of 1,45 m^{2}a in variant A and B.

4.3.5. Use phase impacts

Average NEDC fuel consumptions for upper class vehicles have been determined with 5,75 l diesel per 100 km and 6,975 l petrol per 100 km.[5] Assuming fuel reduction values of 0,15 l/100 km x kg for petrol engines and 0,12 l/100 km x kg for diesel engines respectively, and no secondary weight reductions, leads to the following fuel reduction values and reductions in fuel consumption:

Table 15: Calculated fuel reduction values for two lightweight hybrid variants.

Variant	Petrol	Diesel
Lightweight hybrid variant A	-0,002355 l/100 km	-0,001884 l/100 km
Lightweight hybrid variant B	-0,00201 l/100 km	-0,001608 l/100 km

Table 16: Fuel economy values considering fuel reduction values of hybrid variants.

Variant	Petrol	Diesel
Aluminium baseline	6,75 l/100 km	5,975 l/100 km
Lightweight hybrid variant A	6,747675 l/100 km	5,973116 l/100 km
Lightweight hybrid variant B	6,74799 l/100 km	5,973392 l/100 km

The numbers displayed above show that the weight reduction achieved through either lightweight component only lead to insignificant fuel reduction values and, subsequently, to a negligible reduction of fuel economy values. If, however, secondary weight reductions can be achieved, e.g. by replacing more than one conventional roof cross beam in the body with a hybrid material, higher fuel reduction values of 0,35 l/100 km x kg for petrol engines and 0,28 l/100 km x kg for diesel engines respectively could be assumed, leading to the following fuel reductions and reduced fuel economy values:

Table 17: Fuel reduction values considering secondary weight reductions.

Variant	Petrol	Diesel
Lightweight hybrid variant A	-0,05495 l/100 km	-0,004396 l/100 km
Lightweight hybrid variant B	-0,00469 l/100 km	-0,003752 l/100 km

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[5] These values have been determined by an average based on NEDC information for the following vehicles: Mercedes Benz E-300, Audi A6 3,0l TDI / 2,0 TFSI, BMW 530, Volvo V90 with power output ranging between 150 and 200 kW for the respective petrol and diesel engines.

Table 18: Fuel economy values considering secondary weight reductions.

Variant	Petrol	Diesel
Aluminium baseline	6,75 l/100 km	5,975 l/100 km
Lightweight hybrid variant A	6,69505 l/100 km	5,970604 l/100 km
Lightweight hybrid variant B	6,74531 l/100 km	5,971248 l/100 km

The values indicated in the above tables show that weight reductions of 1,57 kg for the first hybrid lightweight variant and 1,34 kg for the second do not lead to any significant reductions in fuel economy. It should be mentioned at this point that, judging by the insignificant change in the fuel reduction values and total fuel economy, the application of lightweight components in this small scale does not seem to change the impact over the use phase.

Another approach to calculations regarding weight induced fuel consumption has been described by Kofler and Rohde-Brandenburger. Using their formula to determine the weight-induced fuel consumption within the boundaries of the NEDC, a fuel consumption of 0,15 l/(100 kg x 100 km) for petrol engines and 0,12 l/(100 kg x 100 km) can be derived. This can be used to break down fuel consumption per kg part weight. In case of a part that weighs 2,5 kg, the fuel consumption amounts to 3,75 ml of petrol per 100 km (Koffler & Rohde-Brandenburger, 2010, pp. 131-132).

The formula for petrol engines corresponds to:

$$\frac{0{,}15\ l}{100}/(100\ km\ x\ kg)\ x\ part\ weight = weight\ induced\ fuel\ consumption\ [l]. \tag{3}$$

And for diesel engines:

$$\frac{0{,}12\ l}{100}/(100\ km\ x\ kg)\ x\ part\ weight = weight\ induced\ fuel\ consumption\ [l]. \tag{4}$$

The result is the weight-induced fuel consumption per part and per 100 km. It has then to be multiplied with the respective volumetric energy density and by 2000 (200.000 km divided by 100 km) to give the total part weight induced fuel consumption. The volumetric energy density is given with 30,5 MJ/l for gasoline and 35 MJ/l of diesel.

The following numbers representing the weight-induced use phase fuel consumption can be calculated using this method.

Table 19: Weight-induced fuel consumption.

Component	Petrol	Diesel
Al baseline roof cross beam Weight: 8,61 kg	25,63 l / 781,71 MJ	20,664 l / 723,24 MJ
Hybrid variant A Weight: 7,04 kg	21,12 l / 664,16 MJ	16,896 l / 591,36 MJ
Hybrid variant B Weight: 7,27	21,9 l / 667,95 MJ	17,448 l / 610,68 MJ

To complete the picture, the results in MJ have to be added to the resource depletion values to show the complete impact of the part production and the use phase.

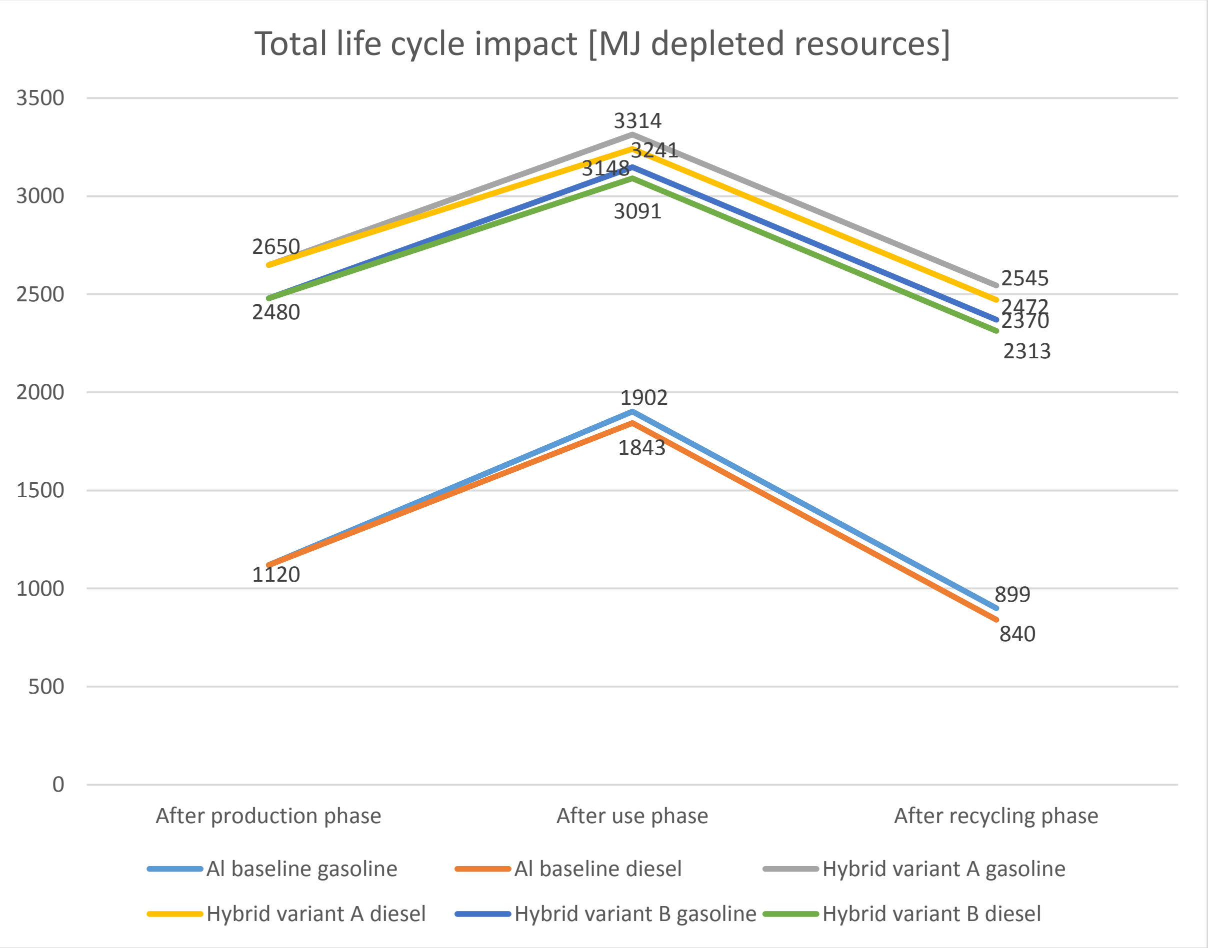

Fig. 25: Total life cycle impact [MJ depleted resources]. Own work.

Fig. 25 shows the complete impacts including the production phase, the use phase over 200.000 km and the recycling phase. It becomes clear that even though the application of lightweight parts result in a significantly lower total fuel consumption of up to 20 %, the use phase and recycling phase cannot counterbalance the production impact, which is why there is no breakeven point visible in Figure Fig. 25. This is also due to the steeper slope of aluminium baseline during the end of life phase. In total, the life cycle impact after recycling is only 300 MJ – 400 MJ lower than the combined impacts of production and use phase of the aluminium baseline part. It is visible that a breakeven point of the lightweight components, at which benefits from the use phase even out the production impacts, cannot be reached during the use phase.

4.4. Interpretation

The results presented in the impact assessment have shown that the CFRP variants generally score worse in every impact category. This is mostly owed to the fact that the hybrid materials require more electrical energy in the manufacture, which leads to great water footprints and land competition values. Additionally, the materials used in the hybrid material scenario do not achieve such high benefits during the recycling phase. The aluminium baseline reaches a total EOL benefit of close to 80 percent referred to the initial energy input. This completely owed to the fact that the aluminium recycling leads to benefits of 1.003 MJ compared to an initial energy requirement of 1.120 MJ of fossil fuels in the production phase. The aluminium part has the essential advantage that it is produced in Canada using 100 % renewable energy sources, and processed in Austria, where the electricity mix at the subsequent processor is also 100 % renewable. This results in relatively low impacts in all considered categories.

The manufacture of the CFRPs for variant A is based in Italy, using the respective electricity mix which has a higher share of fossil fuels in the total energy mix (RePower, 2015). CFRP variant B is produced in Austria, using the national electricity mix. The materials are the transported to a processor in the Czech Republic, which is mainly based on coal, nuclear power and natural gas (Statista GmbH, 2016). These mainly fossil fuel based energy mixes result in a great disadvantage for both CFRP components.

However, it must be said that there several elements are missing in the materials. This concerns information about land use und freshwater consumption in this study. Primary data regarding these indicators were not supplied by any of the suppliers, meaning that the only data available here was taken from ecoinvent and ELCD datasets that have been used within the processes and materials in this LCA. It is also true that the effects on land competition and water consumption are derived from only a few of the processes, namely the production of electricity, while almost none of the single substances in the model leading to impacts regarding land competition or water footprints. This shows that information is not available in sufficient detail, and that results of these two indicators should be used with care, as the only give a vague suggestion to the actual impacts.

The transport distances have been calculated depending on the actual location of the respective suppliers, but have shown to be of lower to insignificant importance to the overall impacts. This is also due to the fact that all transport distances that have been modelled in this LCA are taking place within Europe with lorries as only means of transport.

The life cycle assessment requires more data to add more detail to the model, to show impacts of different material origins, suppliers, processing methods and energy requirements and to become more robust of a model. For the purpose of the study, the assumptions made here are sufficient, but leave room for improvement, e.g. in the recycling model and the detailed production chain of different kinds of aluminium metals. These remarks should be improved in a future model.

5. Research results and discussion

5.1. Variability of results

The results in this study are based on numbers and values that have been determined by the researcher using information from suppliers and in-house experts at Magna as well as studies like this study and literature information. Yet some process data is based on assumptions, because it was not always possible to find a reliable source. Therefore, an uncertainty analysis and a sensitivity analysis need to be carried out to investigate the uncertainty of variables. There are mainly two options for this in SimaPro:

- Using the built-in uncertainty analysis tool for assemblies based on Monte Carlo method.
- Modifying important parameters in a sensitivity analysis in SimaPro that have direct impact in the calculation of environmental impacts.

An uncertainty analysis has been conducted. The results using the built-in tool have been appended in the annex of this thesis. These include the calculations for all four impact categories for each material scenario. The results range within the 95 % confidence interval. The numbers in this interval include the total life cycle impact of a material scenario in a given impact category, which means that the numbers shown in the figures take into account the impacts from production and the added benefit from recycling. It might be confusing that the numbers are lower than in the figures of chapter 4.3. If, however, for example, the impact to the global warming potential caused during production phase and the correlating benefit of the end of life phase are added together, the numbers will match the results shown in the uncertainty analysis.

The uncertainty analysis is executed using a Monte Carlo calculation inside SimaPro and calculated uncertainty values over the course of 1000 iterations to determine mean values, standard deviation, median and the coefficient of variation. The analysis uses data from datasets to perform its calculation. The user however can add certain information using a pedigree matrix to supply additional information to each process and material information within SimaPro to give more detailed results (Weidema et al., 2013). This pedigree approach is a post-normal approach to assign uncertainty to data certain datasets. The additional information includes specifications regarding reliability of datasets, completeness, temporal correlation, geographical correlation, further technological correlation and sample size (Ciroth, 2013). The uncertainty approach in SimaPro using the pedigree matrix only uses five indicators, as the “sample size” indicator is considered obsolete (Goedkopp et al., 2016).

While each dataset has a base uncertainty, the pedigree matrix adds new uncertainty by multiplying the base uncertainty with additional uncertainty information based upon the mentioned aspects. This way, the pedigree matrix distributions stretch the value distributions on both ends on the uncertainty scale.

Some values have been attributed with additional uncertainty information using the pedigree approach where no other information by suppliers or given sources were available, and the Monte Carlo calculation had been executed again. The additional uncertainty information had no visible impact to the overall result compared to the first calculation, even though some datasets had to be estimated because there was no reliable information available. The answer to this can only be guessed in the number of datasets used in the model that have been attributed with uncertainty information by the practitioner. Only 0,07 % of all datasets in the model at hand could be attributed with such information, leading to negligible change of results in the calculation, even though the model is largely based on primary data from suppliers and manufacturers of the respective parts. It can thus be said that if the predominating datasets used by the model and in the uncertainty analysis are non-generic datasets, it does not seem beneficial to add uncertainty information through a pedigree matrix. If, however this information was to be contained in large life cycle inventory datasets already, the additional benefit would have a tremendous impact on the result.

In contrast to this, a sensitivity analysis can be carried out by manipulating parameters that can be set by the researcher. This enables the practitioner to manipulate certain values to learn about behavioural changes of the model. In contrast to the uncertainty analysis, this method is used to analyse important factors for their overall impact. Important parameters in this LCA have been determined as:

- Recycling quota of aluminium and CRRP recycling to change the benefit of the EOL phase,
- Percentage of cutting scrap during production phase which initially has been set to 50 % shall be changed to higher and lower values,
- The origin of aluminium that is used in the production of the aluminium sheets and die-casts to produce the baseline component.

Two cases were analysed where the percentaged cut-off values have been increase from 50 % to 67 % and decreased from 50 % to 33 %. These decreased values can hardly be achieved in existing process, but the behaviour regarding the impact changes shall nevertheless be shown. Cut-off values between 50 % to 70 % are realistic values especially in the processing of CFRPS. Increasing the percentaged cut-off increases the global warming potential drastically from 108 kg CO_{2eq} to 140 kg CO_{2eq} in the baseline variant, from 217 kg CO_{2eq} to 280 kg CO_{2eq} and from 202 to 257 kg CO_{2eq} in lightweight variant A and B. The table below gives an overview about the behaviour if the cut-off percentage is increased to two thirds or decreased to one third of the initial material input.

Table 20: Changes in global warming potential (GWP100a) CML-IA baseline).

Material scenario	Increase to two thirds material loss	Decrease to one third material loss
Baseline variant	108 kg CO_{2eq} to 140 kg CO_{2eq}	130 kg CO_{2eq} to 91 kg CO_{2eq}
Lightweight variant A	217 kg CO_{2eq} to 280 kg CO_{2eq}	217 kg CO_{2eq} to 185 kg CO_{2eq}
Lightweight variant B	202 kg CO_{2eq} to 257 kg CO_{2eq}	202 kg CO_{2eq} to 174 kg CO_{2eq}

Table 21: Changes in land competition (CML-IA non-baseline).

Material scenario	Increase to two thirds material loss	Decrease to one third material loss
Baseline variant	9,25 m^2a to 10,56 m^2a	9,25 m^2a to 8,10 m^2a
Lightweight variant A	18,6 m^2a to 20,4 m^2a	18,6 m^2a to 17,6 m^2a
Lightweight variant B	18,1 m^2a to 19,72 m^2a	18,1 m^2a to 17,26 m^2a

Table 22: Changes in abiotic depletion (fossil fuels) (CML-IA baseline).

Material scenario	Increase to two thirds material loss	Decrease to one third material loss
Baseline variant	1.120 MJ to 1.404 MJ	1.120 MJ to 977,8 MJ
Lightweight variant A	2.650 MJ to 3.460 MJ	2.650 MJ to 2.220 MJ
Lightweight variant B	2.480 MJ to 3.200 MJ	2.480 MJ to 2.120 MJ

Table 23: Changes regarding water footprint (Berger et al., WDI).

Material scenario	Increase to two thirds material loss	Decrease to one third material loss
Baseline variant	0,958 m^3 to 1,24 m^3	0,958 m^3 to 0,862 m^3
Lightweight variant A	1,220 m^3 to 1,63 m^3	1,220 m^3 to 1,014 m^3
Lightweight variant B	1,160 m^3 to 1,546 m^3	1,160 m^3 to 0,964 m^3

No changes have been made regarding the end of life phase in this case, only production phase parameters were adjusted. Two things become very visible in the above tables:

- The increase of the material cut-off value has a much higher impact than the decrease of the cut-off values. This is supposedly due to the fact that the material loss only has a limited influence the lower the values are set. At some point, which has not been calculated here, a baseline is reached where the influences from other processes overweigh in the total impact. Increasing the parameters to two-third material loss however has such a high impact because the materials lost in this process are very rich in terms of embodied energy, resulting in greater specific impacts.
- It is essential to reduce the material losses during manufacture as much as possible to lower environmental impacts. The fewer material is lost during manufacturing, or the more material can be reused during the production of the semi-finished and final products, the lower the overall impact to the environment.

A second interesting approach is to switch the end of life treatment from recycling of carbon fibre reinforced polymers to incineration. For this analysis, the setup has been changed in SimaPro to model a waste incineration for the incurring plastic waste. The end of life treatment for the aluminium parts remains unaffected as they cannot be incinerated.

Table 24: Changes in global warming potential (GWP100a) (CML-IA baseline)

Material scenario	Benefit generated in EOL treatment	
	Recycling	Incineration
Aluminium baseline	114 kg CO_{2eq}	n.a.
Lightweight variant A	79,4 kg CO_{2eq}	65,2 kg CO_{2eq}
Lightweight variant B	79,9 kg CO_{2eq}	64,6 kg CO_{2eq}

Table 25: Changes in land competition (CML-IA non-baseline).

Material scenario	Benefit generated in EOL treatment	
	Recycling	Incineration
Aluminium baseline	1,30 m^2a	n.a.
Lightweight variant A	-9,41 m^2a	0,687 m^2a
Lightweight variant B	-10,3 m^2a	0,664 m^2a

Table 26: Changes in abiotic depletion (fossil fuels) (CML-IA baseline).

Material scenario	Benefit generated in EOL treatment	
	Recycling	Incineration
Aluminium baseline	1.003 MJ	n.a.
Lightweight variant A	769 MJ	647 MJ
Lightweight variant B	778 MJ	647 MJ

Table 27: Changes regarding water footprint (Berger et al., WDI).

Material scenario	Benefit generated in EOL treatment	
	Recycling	Incineration
Aluminium baseline	0,244 m^3	n.a.
Lightweight variant A	0,216 m^3	0,154 m^3
Lightweight variant B	0,220 m^3	0,153 m^3

Modifying the end of life treatment to incinerate materials instead of recycling them after the use phase shows to have an important impact to the overall performance of the materials. Even with higher expenditures during the recovery of carbon fibres, the GWP100 benefit of lightweight materials is still 18 % higher than any benefit from incineration. In combination with the problems regarding combustion of carbon fibres, as mentioned earlier, incineration does not seem to be a convincing alternative.

Moreover, a modern recycling and recovery scenario also seems beneficial in terms of the water footprint and abiotic depletion, in which the lightweight materials achieve higher benefits from recycling. On the contrary, an incineration of carbon fibres achieves a much better performance in the land competition indicator, in which the carbon fibre recovery suffers from the energy-intensive processing, caused by the heat treatment in the oven. This could be an argument for incineration. However, this completely neglects all downsides related to the incineration that have been mentioned before. In addition to that, the calculation in SimaPro for land use changes are exclusively based on the demand of electrical energy. The land use change indicator does not comprise other materialistic inputs other than electricity. Fibre recovery requires 15 kWh per kg of carbon fibres in this model, against what the incineration requires none, which is why the incineration process apparently leads to better results. The incineration process also disregards the fact that the material is lost and cannot be recovered, which cannot be said about the recovery process.

The same argument is also valid in case of the water footprint, where benefits from recycling are reduced to around 70 % of the original credit. This is also because the water footprint is mainly caused by electricity generation. A great amount of energy is required in the production of CFRPs, which, in the LCA model, is then accounted for as embodied in CFRP products and lost if materials are incinerated. This material loss translates in lower benefits in the EOL phase.

It could be argued that - based on the arguments presented in chapter 3 and 4 - incineration should not be considered as an EOL strategy here. This is true, and shall be underlined in this scenario especially by applying the incineration scenario, because it shows that the benefit from incineration is much lower than the benefit generated in a recycling scenario. It shall also be repeated here that incineration is not an option, as waste incineration plants have begun refusing acceptance of CFRP waste as combustible materials due to problems they cause during the combustion as stated in chapter 4.

A third variable was already mentioned as the origin of the aluminium can be a great factor. If the origin is changed from a Canadian supplier to Asian supplier, e.g. India, leaving the production of the CFRPs in Europe unchanged, the impacts caused by a change of the electricity mix, different production efficiency or changed delivery distances can be determined. Therefore, the model was changed to use aluminium from Indian supplier. This was done by changing the origin from Canadian aluminium (CA-QC) to aluminium (IAI Area &5 without China, production).

There were no datasets for aluminium casts of explicit Asian origin available, so a production using Rest of World (ROW) aluminium cast, representing a mix of the world production, was chosen. Fig. 26 to Fig. 29 compare the changed baseline version to the unchanged lightweight variants.

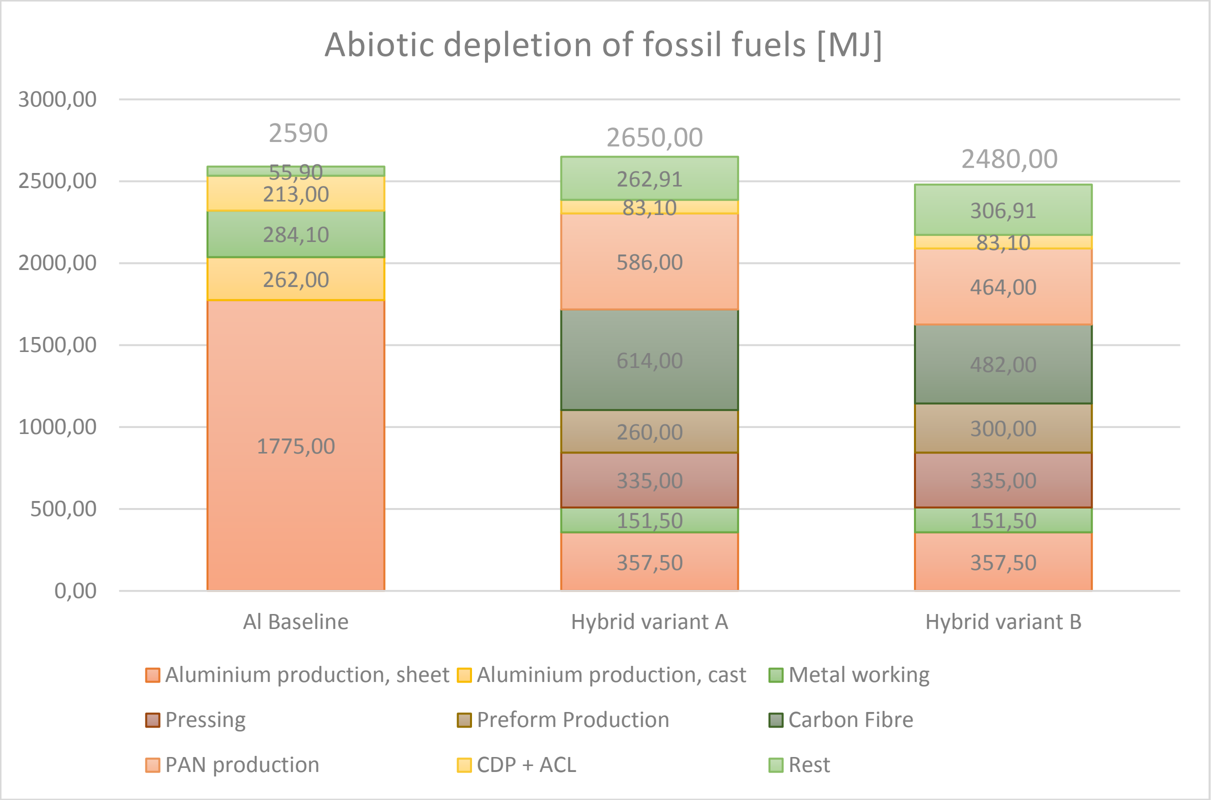

Fig. 26: Changes in abiotic depletion of fossil fuels caused by change of aluminium origin.

It becomes clearly visible that the impact of the aluminium baseline is heavily dependent on the origin of the aluminium. The great advantage of the aluminium in all categories was caused due to the electricity mix during at the aluminium smelter. The two most important indicators, depletion of fossil fuels and global warming potential, have more than doubled (Depletion of fossil fuels, Fig. 26: 1.120 MJ to 2.590 MJ; GWP100a, Fig. 27: 108 kg CO_{2eq} to 265 kg CO_{2eq}) in their outcome.

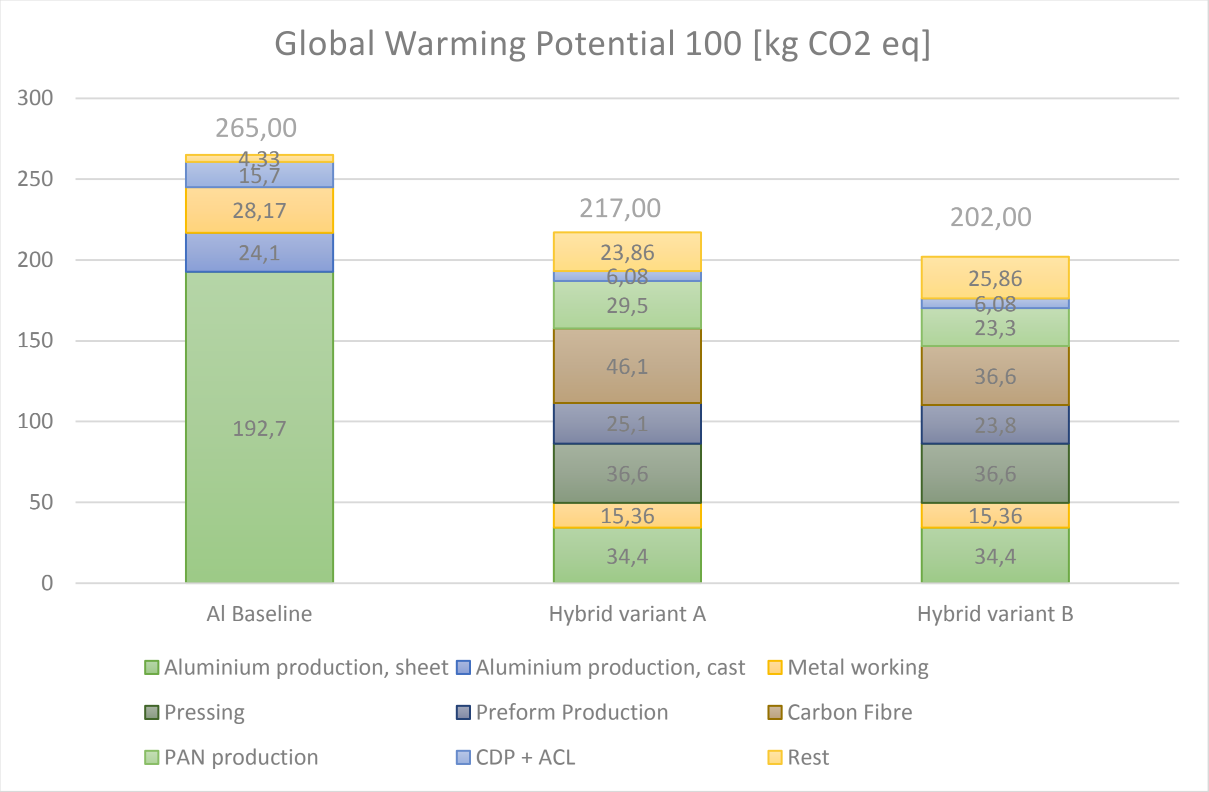

Fig. 27: Changes in global warming potential caused by change of aluminium origin.

There are two remarks that should be clarified to understand the EOL benefit of the aluminium baseline. The aluminium is assumed to be produced in India. Higher fossil fuel depletion in the production leads to a higher global warming potential as it has been shown in Fig. 26 and Fig. 27. After subtracting the EOL credit, achieved by aluminium recycling, the *remaining* global warming potential is still high, whereas the EOL benefit from aluminium recycling usually reduces the total global warming potential by around 85 to 90 %. This is not the case here because the waste treatment assumes a European recycling scenario, in which the initial production related GWP is assumed to be lower (~50 % as in the case of the baseline variant). Furthermore, the waste aluminium is mixed in the waste stream, so that waste metal from outside the EU do not achieve higher recycling benefits.

A solution to this problem would be to export the material back to its country of origin, where its reduction potential at end of life stage would be far higher due to correctly sorted inputs at the recycling stage and could be credited accordingly.

The following Fig. 28 shows the results resulting from a different origin of the aluminium in the baseline scenario.

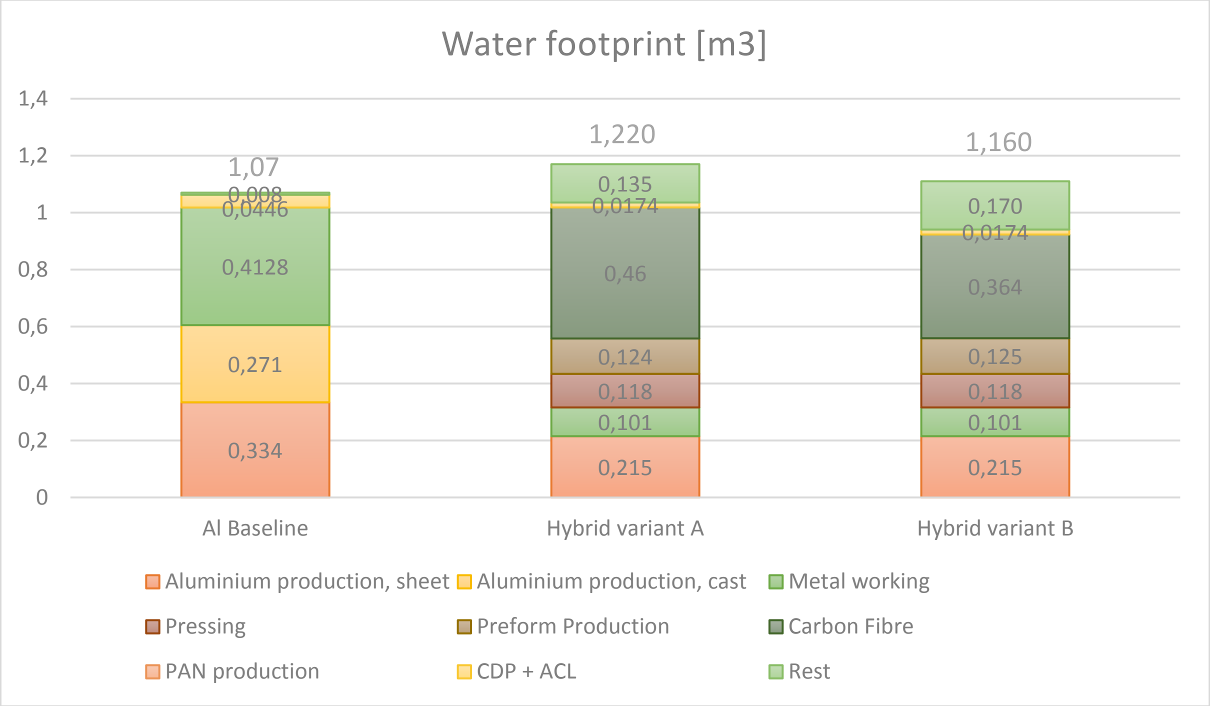

Fig. 28: Change of water footprint caused by change of aluminium origin.

There have been significant increases in the water footprint (Fig. 28: 0,958 m^3 to 1,070 m^3) and in the land competition (Fig. 29: 9,25 m^2a to 11,30 m^2a). The lightweight material scenarios now seem very competitive from an environmental point of view, especially regarding the global warming potential, where the aluminium baseline has considerably higher impacts. Hybrid variant B, using recycled CFRP cut-off materials during manufacture, is now more competitive in two impact categories (fossil fuel depletion, GWP), and scores only slightly higher in the water footprint impact category (1,16 m^3 compared to 1,07 m^3 aluminium baseline).

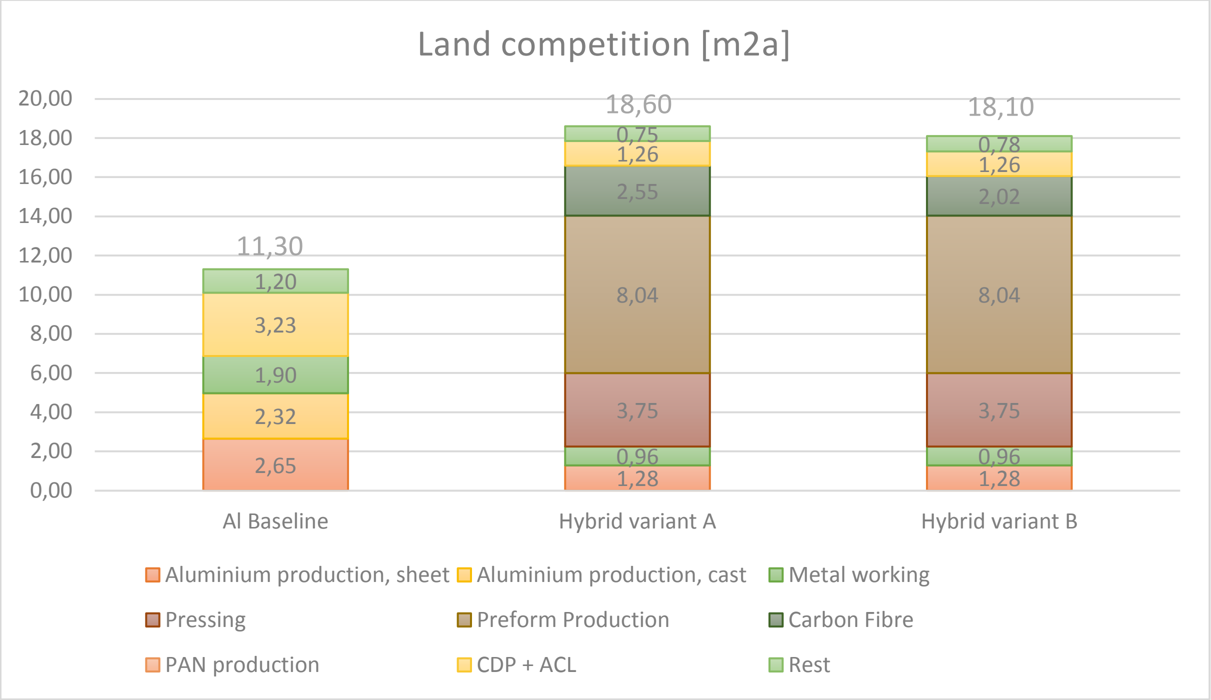

Fig. 29: Change in land competition caused by change of aluminium origin.

However, it can be said that lightweight construction materials have a quite competitive environmental performance. This becomes visible in case the aluminium loses the advantage of environmentally friendly production through renewable energy. Like carbon fibre reinforced plastics, the production of primary aluminium is associated with a very high primary energy expenditure. Primary aluminium production requires an average of 15.000 to 16.000 kWh per ton (15 – 16 kWh/kg) (Dienhart, 2003, pp. 5-7), where in contrast the production of 1.000 kg of carbon fibres requires 100 kWh (0,1 kWh/kg) according to the Italian supplier. Both, the aluminium and carbon fibre production, are prone to changes in the energy mixes used during the production. The statement that the production of CFRPs is associated with high environmental impacts can thus not be assumed if the production of the fibres takes place under conditions similar to those of aluminium production.

5.2. Influence of LCA results in corporate decision making

The following section represents a summary of important that have been mentioned in personal discussions with several persons in charge at Magna Steyr in response to the question of how influential LCAs can be in corporate decision making. The challenge of environmental-friendly product development is often not directly the assessment of product-related impacts, but the integration of assessment methods into the early development and design stages. Modelling tools and inventory databases have become very powerful and exhaustive, making the assessment a manageable task. But when life cycle assessments have been carried out, the key question remains if LCA results can incorporated in the decision-making process. If not, then how should results be communicated and integrated in corporate processes to sensitise its employees?

A dilemma of LCAs is their complexity, and that results represent aggregated numbers to which different professional fields cannot easily relate. While the concept of *Carbon Dioxide Equivalents* or *Total Primary Fossil Fuel Depletion (MJ)* of a given product are rather comprehensible terms, midpoint indicators such as *Ecotoxicity, Photochemical Oxidation* or *Infrared Forcing* cannot be communicated without further explanation. Even endpoint indicators such *Human Health (DALY), Ecosystems Species per Year* or *Resources Surplus Cost* according to the ReCiPe method cannot be interpreted so easy. The core issue here is the difficult communicability of LCA results and their specific meaning. While the LCA community continuously enhances and refines methods and approaches, the essential problem of LCAs remains understanding the meaning of the results outside of the scientific circle such that it can be made sure that those in charge are capable to comprehend the effects a certain choice, e.g. of a material or production process, can entail.

Furthermore, there is the particular problem of the automotive supplier industry that a distinction must be made between series development and research and development projects. In case of the series development, a margin for material selections rarely exists, as the choice is left to the customer, usually the OEM. Looking at the decision cascade in such projects, LCA results are almost always positioned behind crucial automotive criteria such as quantity of units, cost of the concept, weight distribution, driving dynamics or comfort (Kaufmann & Goetzinger, Interview Regarding Effects of LCA Results in Corporate Decision Making, 2016). It should, however, be assumed that a decision-supportive LCA has been carried out at the OEM for a range of different materials. The execution of an LCA is not contained within the specifications of an automotive project, and LCA results of automotive products are not demanded by the OEM.

In opposite to series development, research and development projects leave more room to incorporate results from life cycle assessments. In case of Magna, life cycle assessments are required and part of the ecodesign approach to environmental-friendly product development which must be reported in every research and development project (Hofer & Harmusz, 2016). Furthermore, an Environmental Performance Indicator (EPI) has been developed to assess the environmental performance in the automotive development. This EPI relates the number of complete vehicle development projects to the number of ecodesign projects, with the eco-political goal for this number to converge to one. Another useful approach here could be a mandatory implementation of sustainability checklists during early project phases that answer questions regarding sustainability aspects, and the integration of material assessments by means of an LCA if applicable (Mayr, 2016).

Nevertheless, the production of an LCA and their results are a first and important step in the awareness raising in product vision and design, because it is the bone of contention for a discussion about environmental impacts of products and different materials. As a matter of fact, it is not often the numerical result which is important, but the fact that an LCA has been carried out for a certain product or a material than can later be used as a baseline for future products and serve as a benchmark for other projects (Hofer & Harmusz, 2016). They are considered an important tool to draw a complex but informative picture of environmental and technical links. A further valuable approach could the implementation LCA datasets inside the product data management, to an extent that possible environmental impacts of different materials become visible to the actual developer, leading to discussion and the examination of different material solutions in focus (Stadler, 2016).

In can be summed up that LCAs are an important tool in the assessment of automotive concepts. But, depending on the type of project, wether it affects a serial production or a development project, the effects and influences are different, and very limited in the first case. Still, even though LCAs are often not a top priority, they do lead to a discussion and an increase of awareness in terms of environmental responsibility in the automotive development.

5.3. Future goals

An essential future goal for future LCAs should be to increase the availability of data. Close contacts to suppliers in the automotive industry should help to obtain more data. The data used in this thesis has been collected over a time horizon of more than half a year with help of internal and external contacts. It has also helped that there was already much information available on aspects such as the production of metal components, material suppliers and supplier routes. There was also a lot of information available regarding the in-house cataphoretic dip painting at Magna's plant in Graz.

Because SimaPro's databases already included a lot of material and process datasets, it was possible to conduct this LCA to this extent in the time of six months. However, a longer time period will be required to gather data where supplier contacts have not been established yet. Data acquisition and quality will always be crucial aspects within LCAs, not only because gathering information is a very time consuming part, but also because data quality has immense impacts on the results. The more granular processes can be created within the modelling, the more precise results will be.

In this LCA, a lot of assumptions had to be made, often simply because there was not enough information available from industrial processes or due to the fact that some processes only find themselves to be at laboratory scale, e.g. the pyrolysis in the end of life treatment of carbon fibre reinforced polymers. A goal here should be to follow with great attention the development of recycling methods, because carbon fibre is already produced in amounts that simply cannot be landfilled. Neither can they be incinerated due to the problems they cause during combustion as stated in chapter four.

A further goal should be the creation of an inventory based on Magna's internal processes in order to obtain an accurate picture of the manufacturing situation at the various locations and to be able to build future LCA models based on local processes in a realistic manner and shorter time scale. Magna at the Graz location is in the excellent position not only to house the complete vehicle development, but also to carry out the actual vehicle manufacture in a comprehensive framework. This advantage should be exploited to become more independent of external processes in future LCAs, so that only remaining information needs to be collected coming from specific external products, production processes of respective suppliers or to take into account national peculiarities.

This life cycle assessment had as a goal to assess the land use and water footprint of automotive products. The sheer amount of studies assessing water footprints or land use in relation to the amount of studies found dealing with classic impact categories such as global warming potential and resource depletion shows that it is still very difficult and time consuming to assess these impact categories. None of suppliers that have made available primary data in this LCA included information regarding actual water consumption or land use in their datasets. The goal should be to motivate suppliers to gather this data where available, especially because freshwater use is an indicator that can be determined with manageable efforts.

Information concerning the land competition could only be taken from ecoinvent datasets. Furthermore, available data in ecoinvent refers exclusively to impacts caused by the production of electricity. Impacts caused by the actual drivers behind environmental effects, i.e. products and partial products, were not allocatable because values for land competition are currently not modelled in the majority of used processes and products.

Chemicals based on petroleum products had little to no impact to the land competition, which is highly doubtful as the production of petroleum and petroleum-based products require huge amounts of land areas that often compete with agricultural uses. This is visible, for example, in the production of heavy crude oil in California, US, or the extraction of oil sands in Alberta, Canada (Yeh et al., 2010). Even if the production of the polyacrylonitrile precursors is located in Europe using natural fibres as precursor, land competition will still occur because of agricultural competition for land areas. This would have been interesting to see in the study of Rosa et al., because they assessed the impacts of natural hemp fibre production.

Future goals here need to be the integration of more datasets into databases such as ecoinvent, ELCD or even USLCI. The methods for land use assessment are important, but they are hardly applicable if process datasets do not contain usable information.

6. Conclusion

This thesis has assessed the environmental impacts of three material scenarios of a structural vehicle component in four impact categories. The methods and impact categories were chosen because not only do they represent important impacts to the environment, but also because they are expressed in units that are considered comprehensible in their meaning.

Understandability, apart from the actual results themselves, is an essential aspect in life cycle assessment. Fact-based results do not help understanding the bigger picture if they cannot be communicated and understood. Therefore, the author chose the indicators at hand.

Based on primary and database values, the impacts of three given material scenarios were determined. The main result here was that the aluminium baseline variant has a better environmental performance. The reason for this has been found in the environmental friendly production of aluminium raw materials, and there mainly because of the use of renewable energy sources.

The material production for lightweight components was modelled with production and downstream processing located in Europe. This lead to an environmental performance of the assessed products that did not support the choice of lightweight materials in vehicle manufacture.

However, as the scenario was changed from environmental friendly material raw material extraction and production of Canadian aluminium to a raw material acquisition and metal production taking place in Asia, environmental performance turned out to be much worse for the aluminium variant, with the lightweight materials suddenly becoming very competitive to the aluminium variant. With this knowledge, it cannot be claimed that the production and application of lightweight materials is automatically accompanied with severe environmental impacts.

Further research is needed here to assess the impacts of carbon fibre production which is completely based on renewable energy sources. A step further could also be taken here by expanding the assessment, and assuming the use of natural hemp fibres as precursor material for the carbon fibre production, as previously shown in the study by Rosa et al.

This study has shown how different material scenarios perform on environmental level. The life cycle assessment study produced in this here master thesis is part of prefeasibility project at Magna’s Engineering Center in Graz. The results of this study can now be used to back a material selection based upon the best environmental performance.

The life cycle assessment is an important tool in product life cycle management, which has not been done to this extent yet regarding material assessments. With Magna Steyr having a long history of taking care of environmental aspects by applying multiple approaches, such as balance co$_2$de and eco-design, the life cycle assessment tool SimaPro fits perfectly into the environmental toolbox to learn about potential environmental impacts of products and materials, and to support the environmental-friendly development of automotive products within the earliest development stages.

It must be said though that life cycle assessment is not a solution to environmental problems, but must rather be considered as a powerful tool to increase the environmental performance of products by detecting room for improvement and by offering potential alternatives. To reduce environmental impacts, the top priority should always be to avoid unnecessary consumption in general, minimize material intensity in production and use phase, aim for a design for reparability and recycling was well as the application of the waste hierarchy defined by reuse and recycling before thermal recovery (“waste to energy”) and disposal.

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Appendix/Annex

The following figures show the results of the uncertainty analysis for 4 impact categories and each material scenario. Figures 30 - 41 represent results of the uncertainty analysis without additional pedigree matrix information, figure 42 - 53 include pedigree matrix information which can be recognized by the spread of the interval on the x-axis.

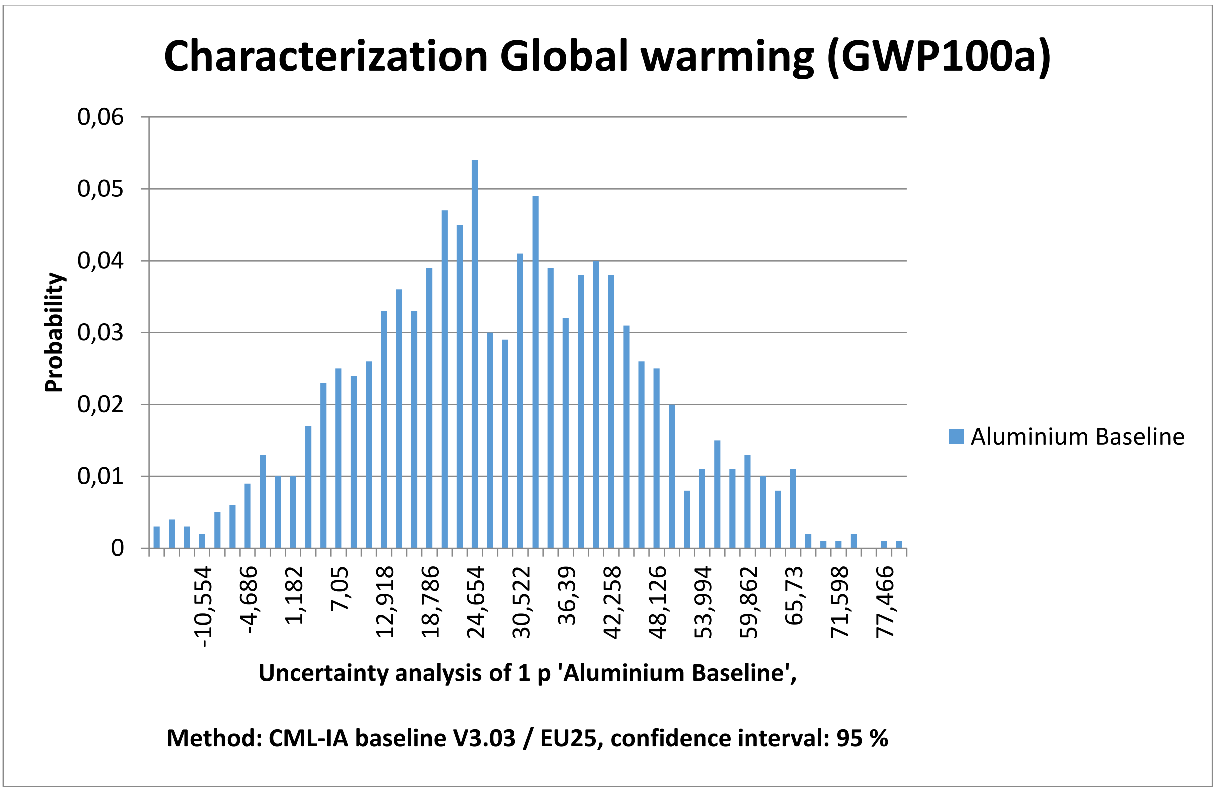

Fig. 30: Uncertainty analysis for aluminium baseline. Indicator: global warming potential.

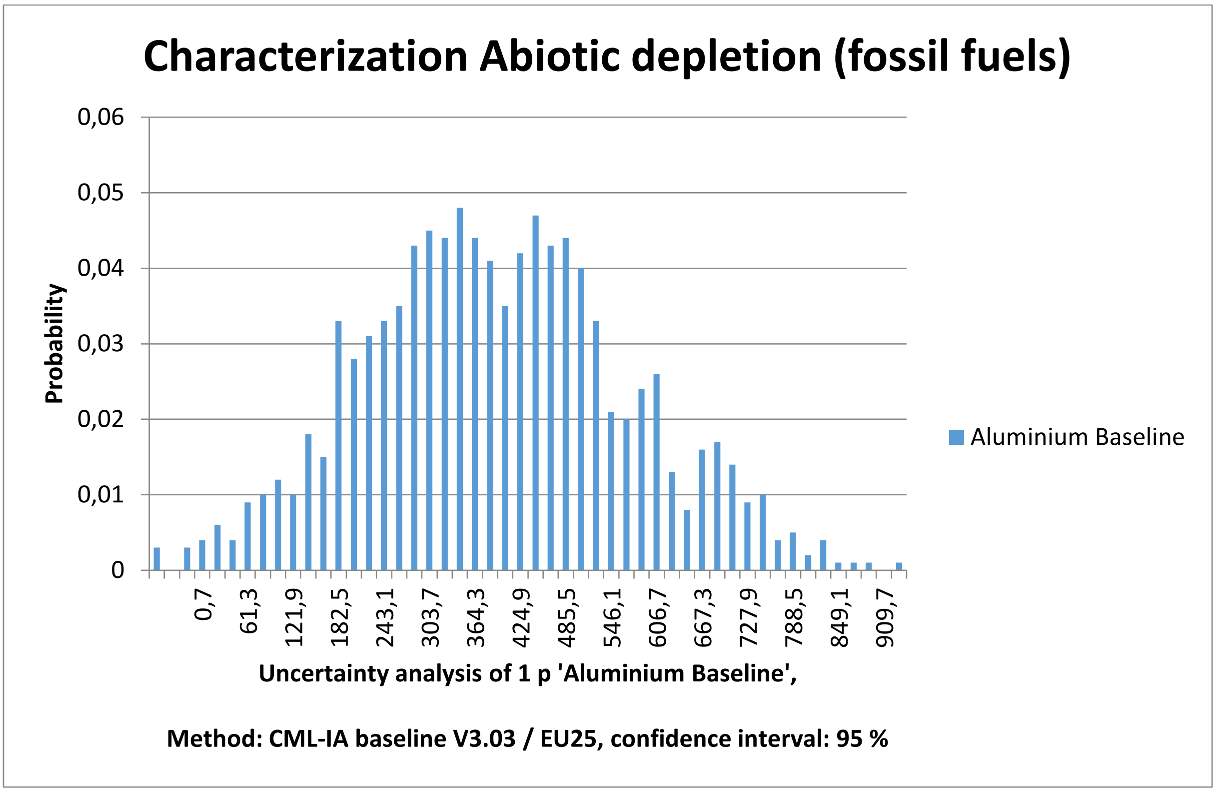

Fig. 31: Uncertainty analysis for aluminium baseline. Indicator: abiotic depletion of fossil fuels.

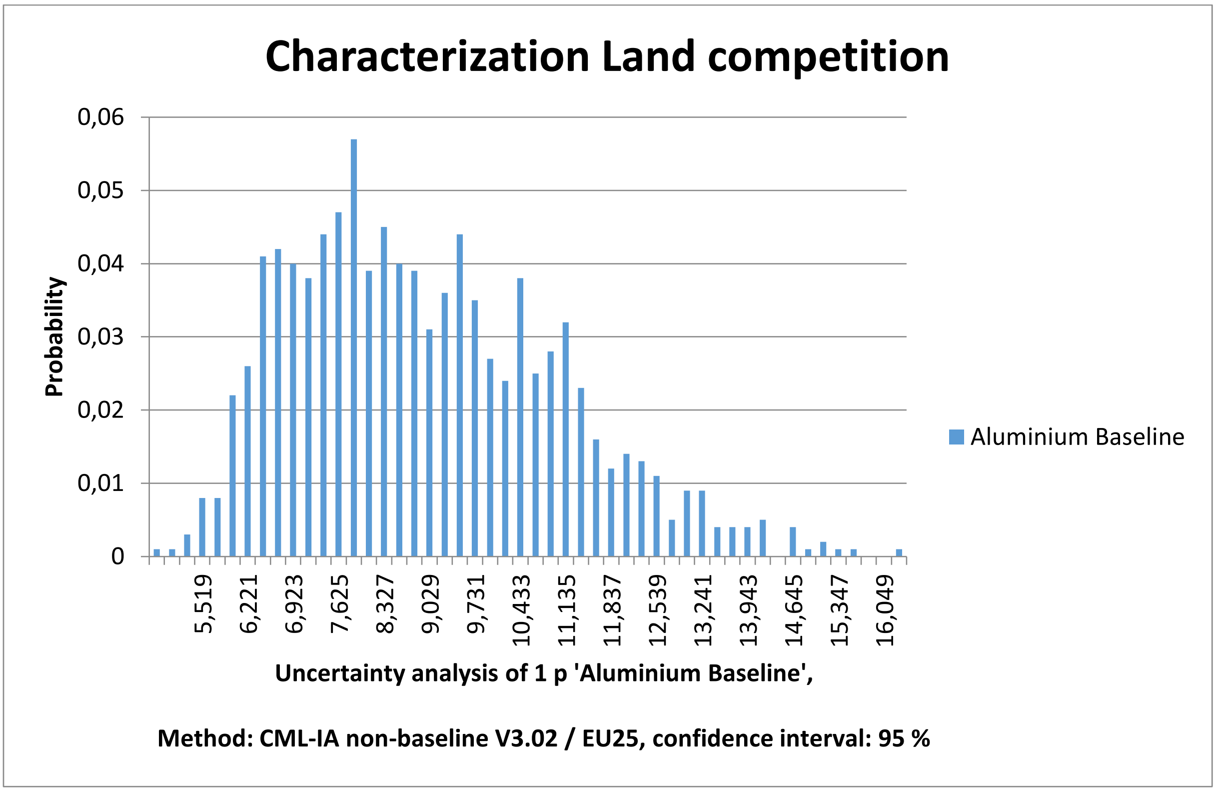

Fig. 32: Uncertainty analysis for aluminium baseline. Indicator: Land competition.

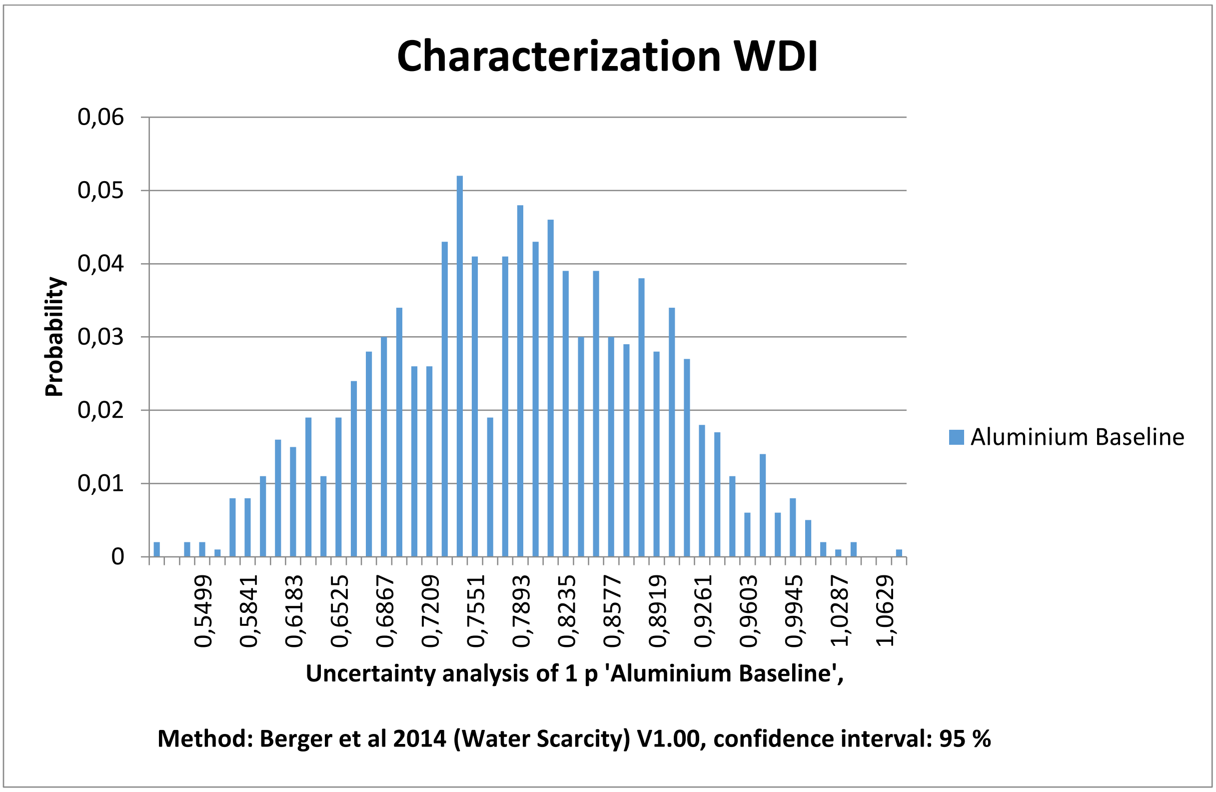

Fig. 33: Uncertainty analysis for aluminium baseline. Indicator: Water footprint.

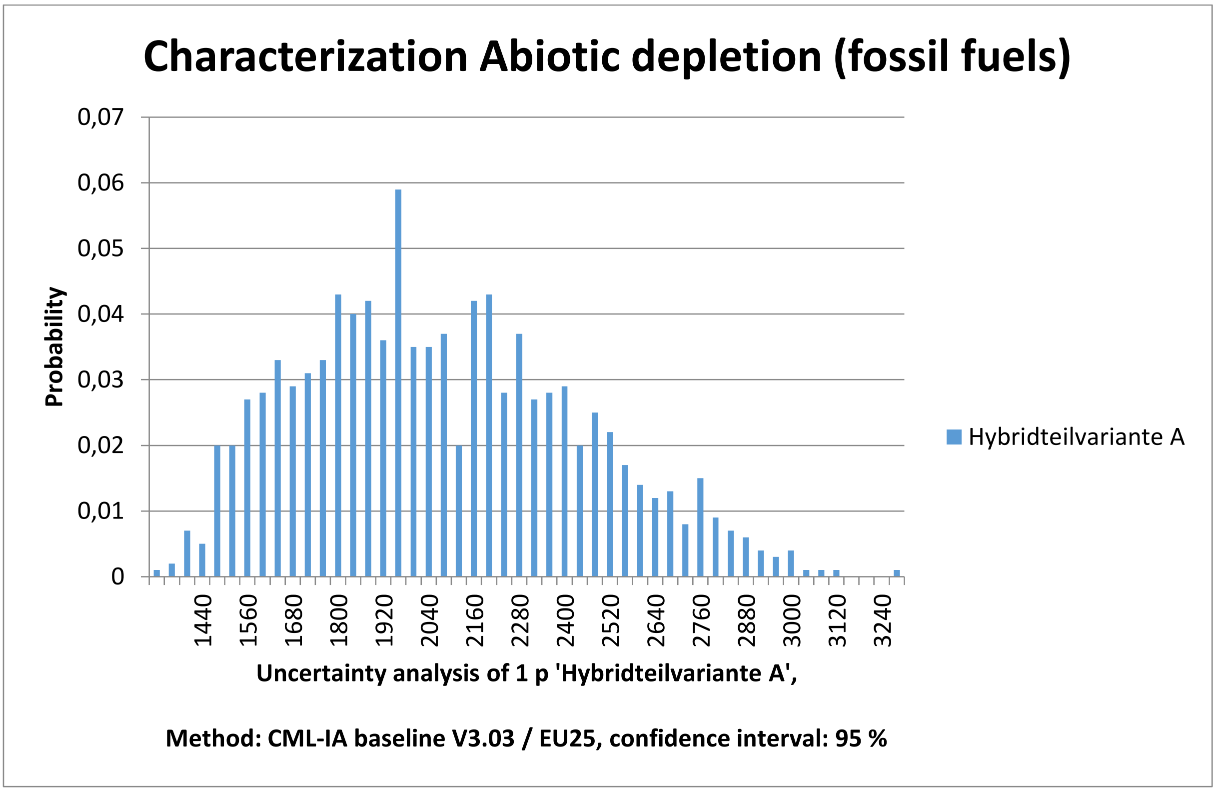

Fig. 34: Uncertainty analysis for hybrid variant A. Indicator: abiotic depletion of fossil fuels.

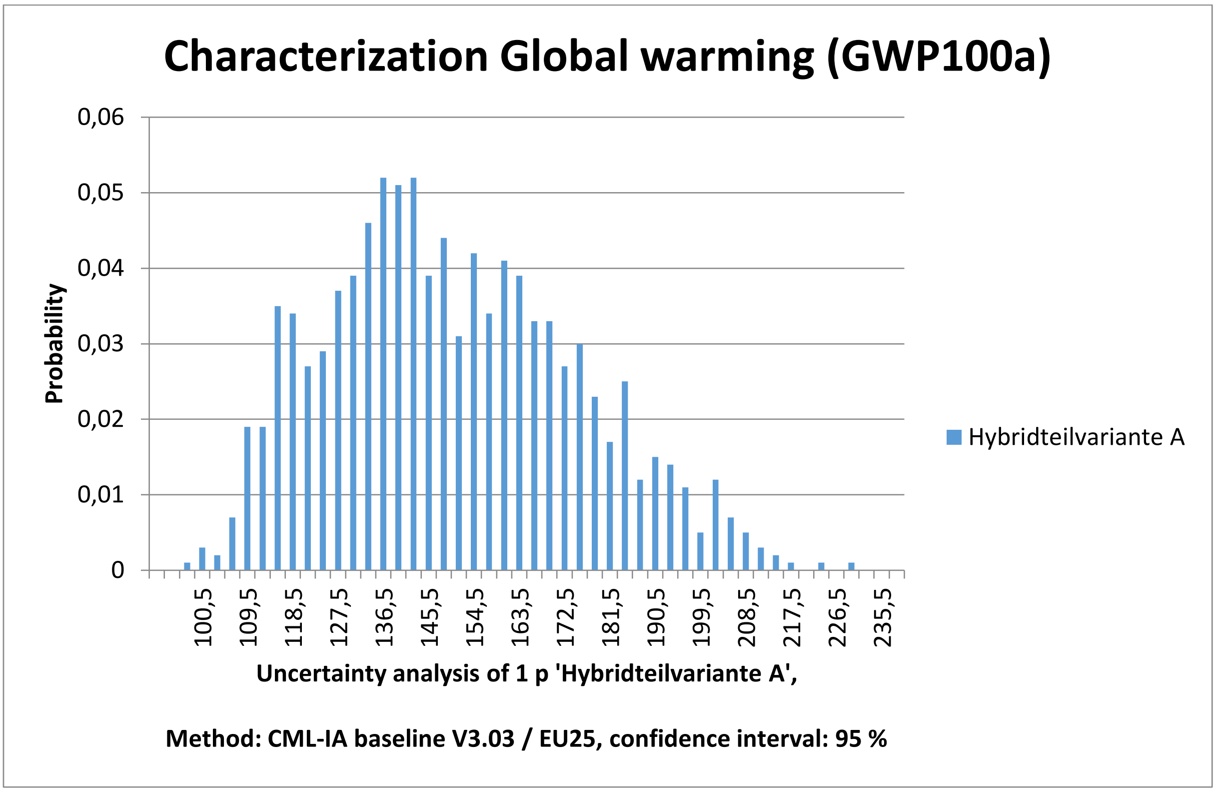

Fig. 35: Uncertainty analysis for hybrid variant A. Indicator: global warming potential.

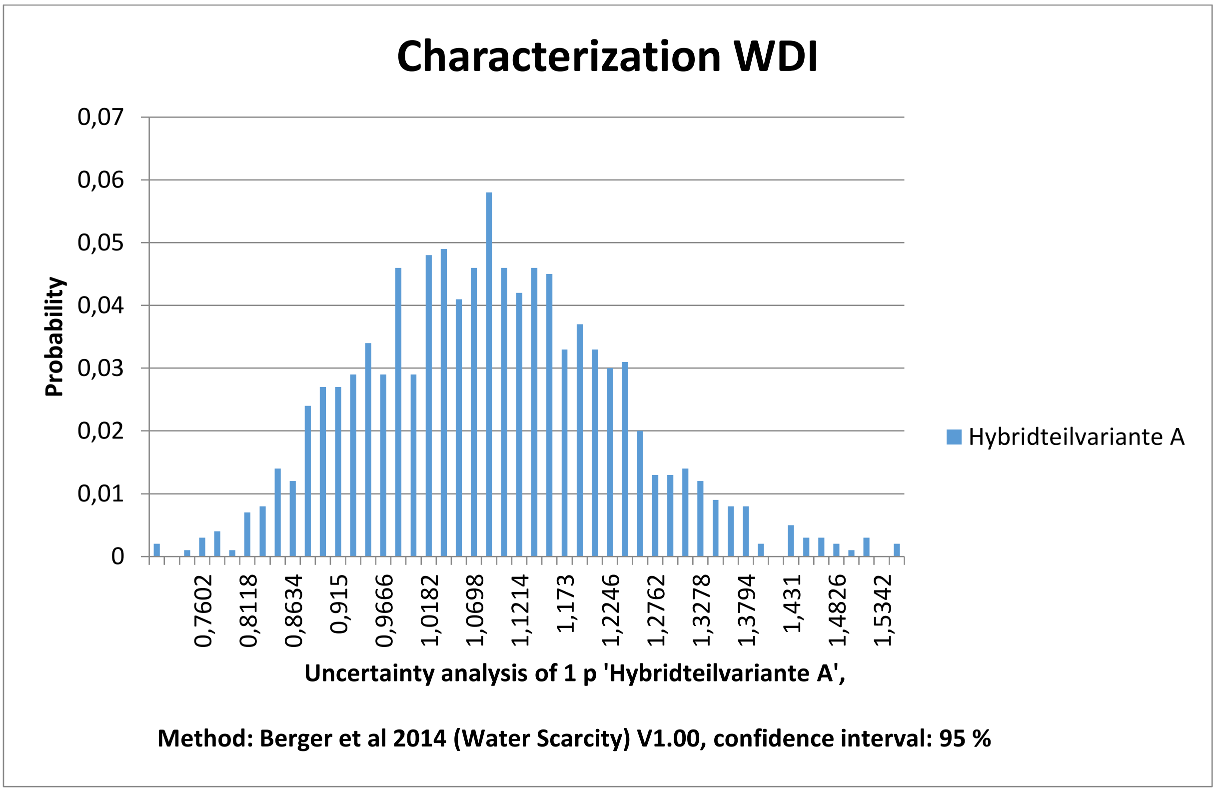

Fig. 36: Uncertainty analysis for hybrid variant A. Indicator: water footprint.

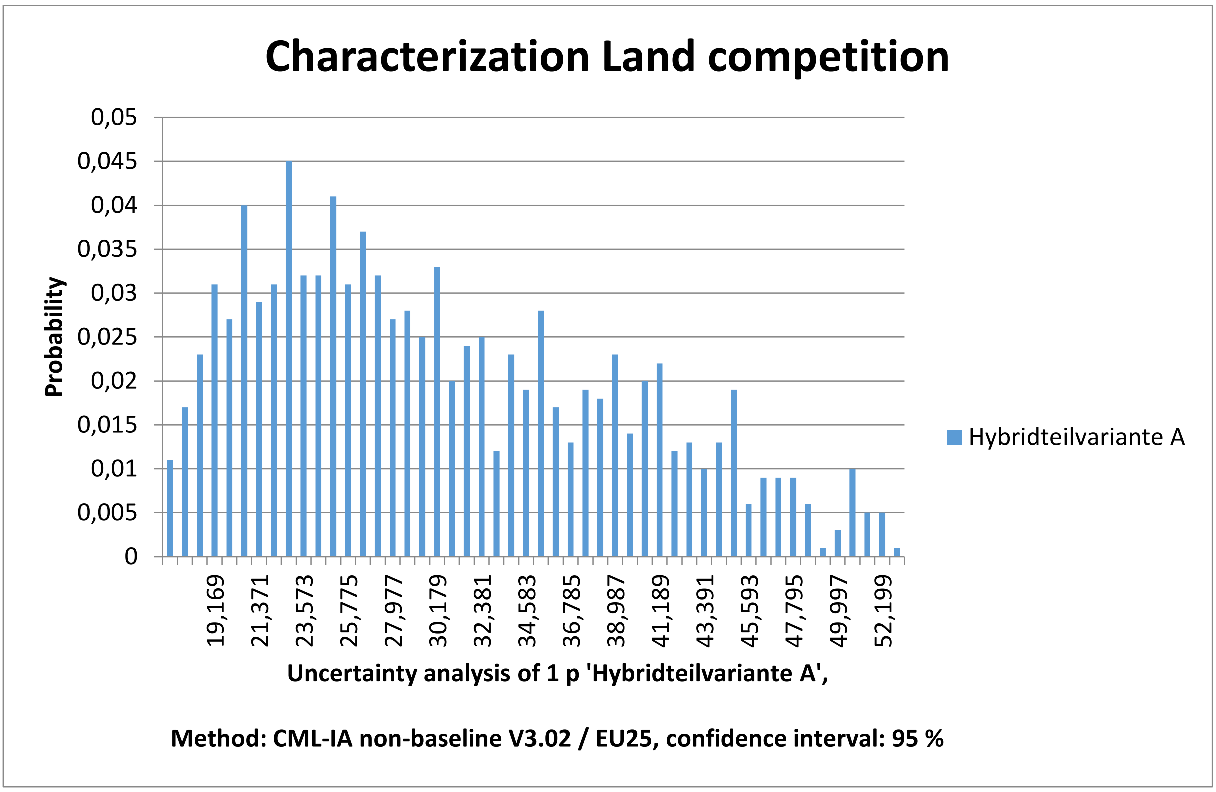

Fig. 37: Uncertainty analysis for hybrid variant A. Indicator: land competition.

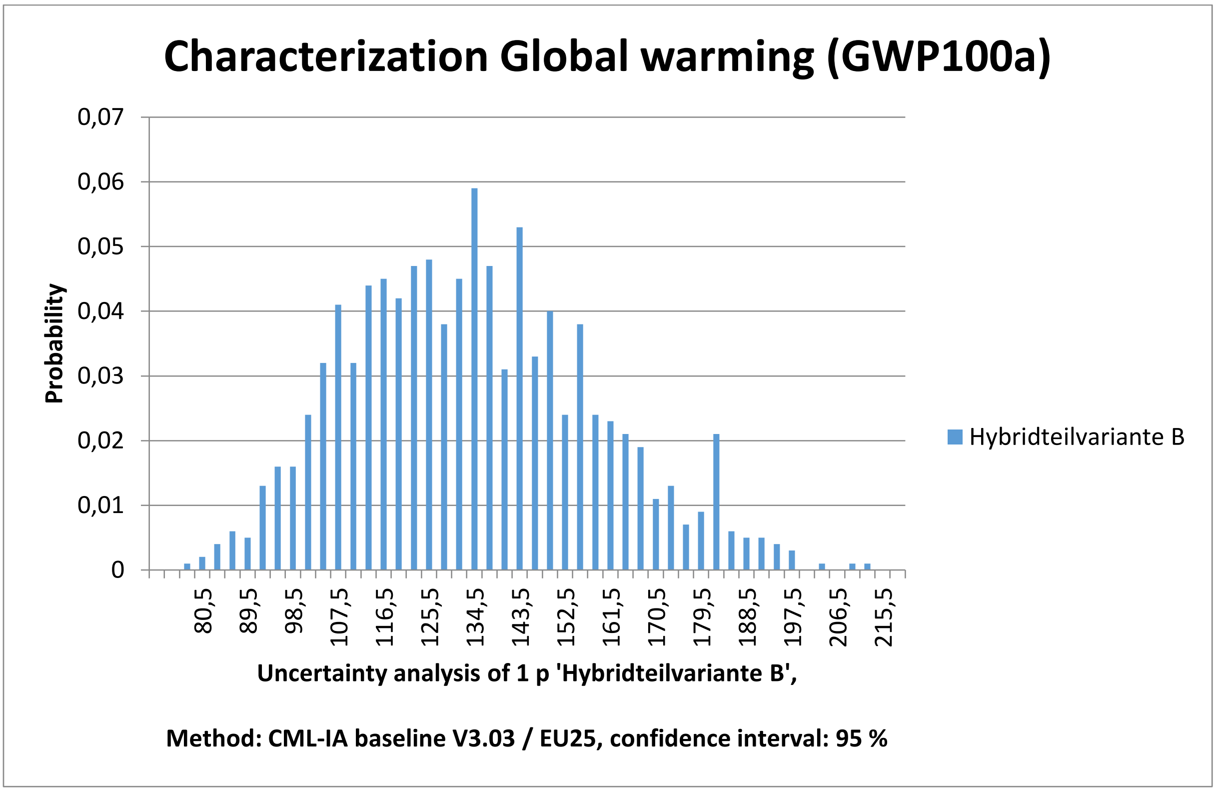

Fig. 38: Uncertainty analysis for hybrid variant B. Indicator: global warming potential.

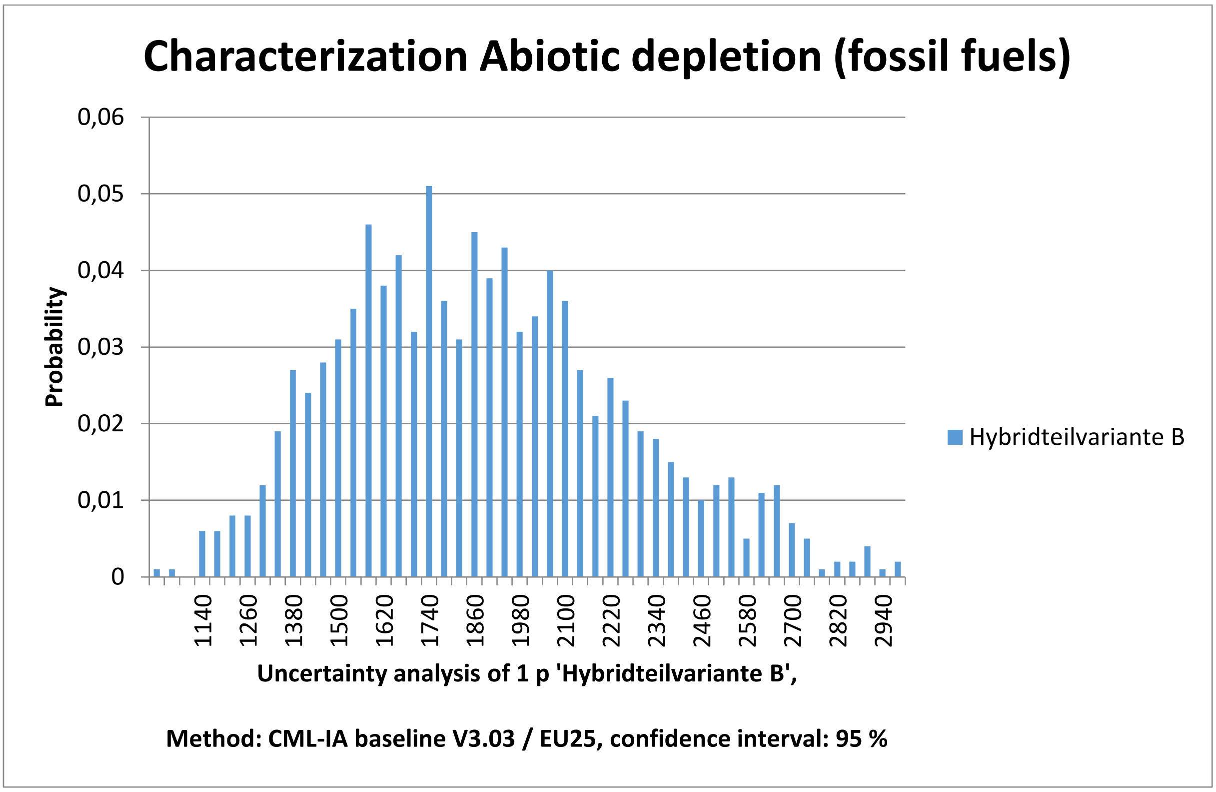

Fig. 39: Uncertainty analysis for hybrid variant B. Indicator: abiotic depletion of fossil fuels.

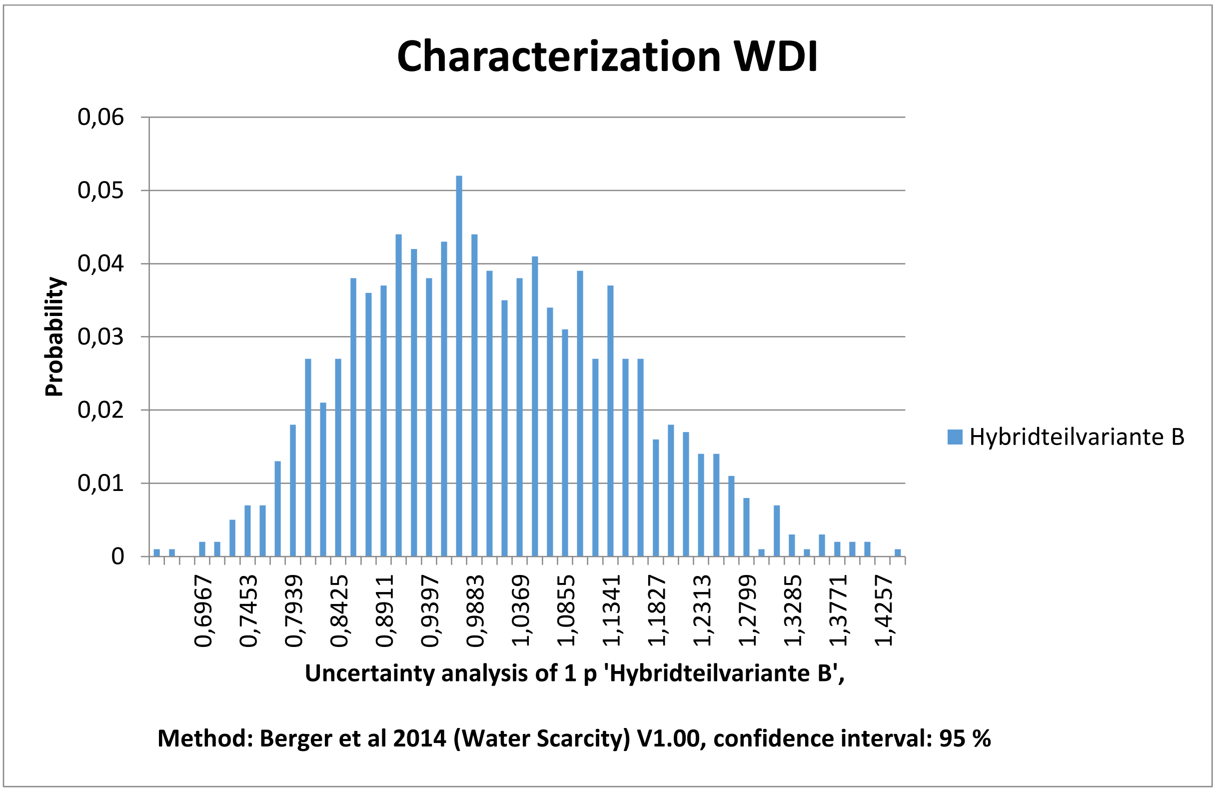

Fig. 40: Uncertainty analysis for hybrid variant B. Indicator: Water footprint.

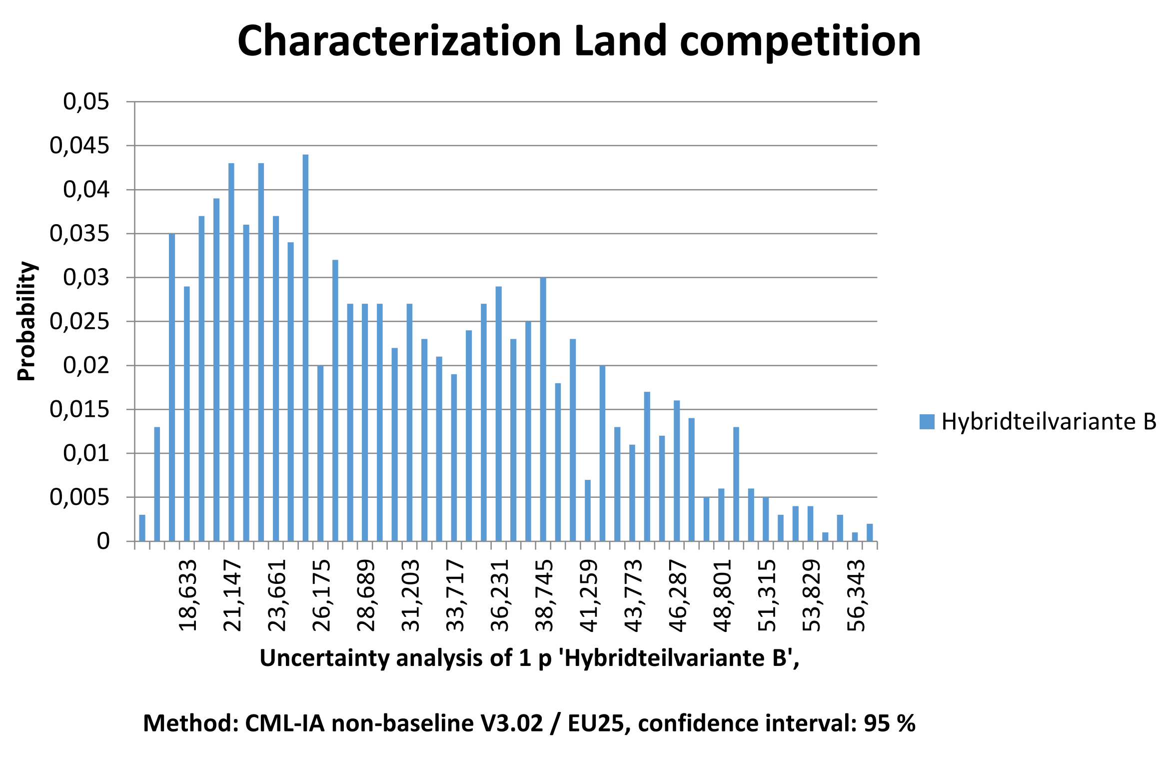

Fig. 41: Uncertainty analysis for hybrid variant B. Indicator: Land competition.

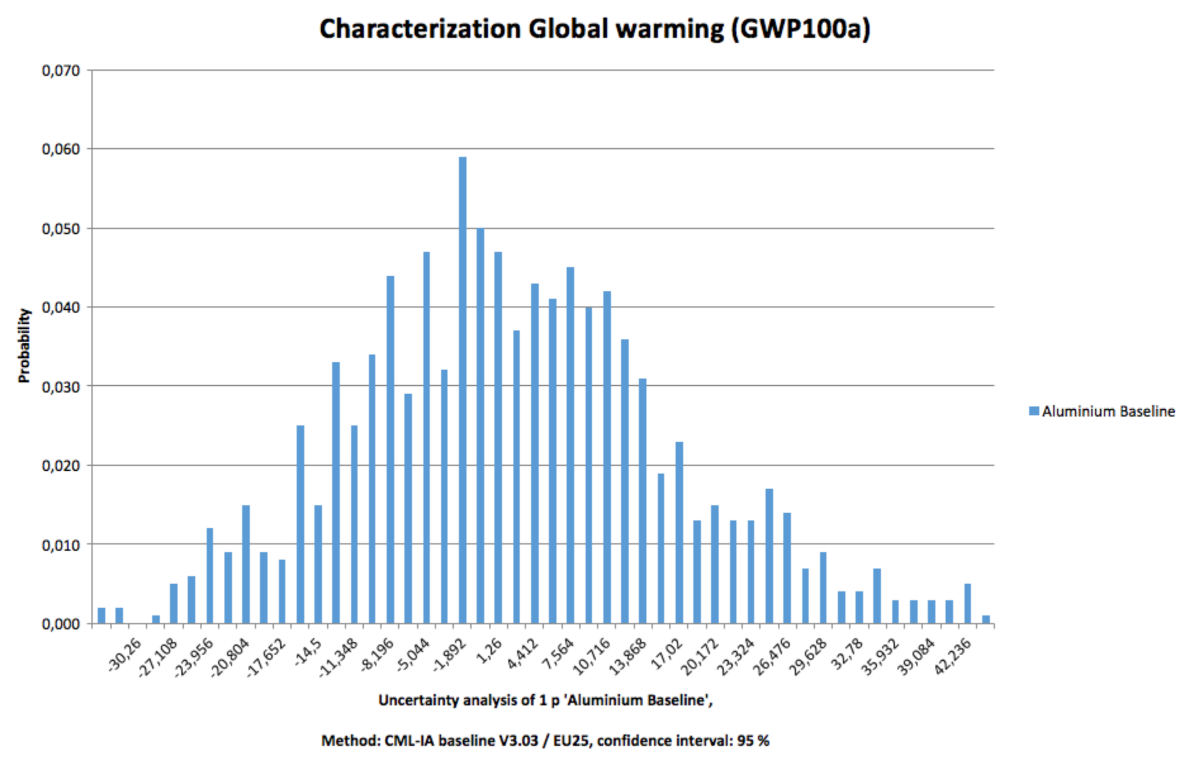

Fig. 42: Uncertainty analysis for aluminium baseline with pedigree matrix. Indicator: global warming potential.

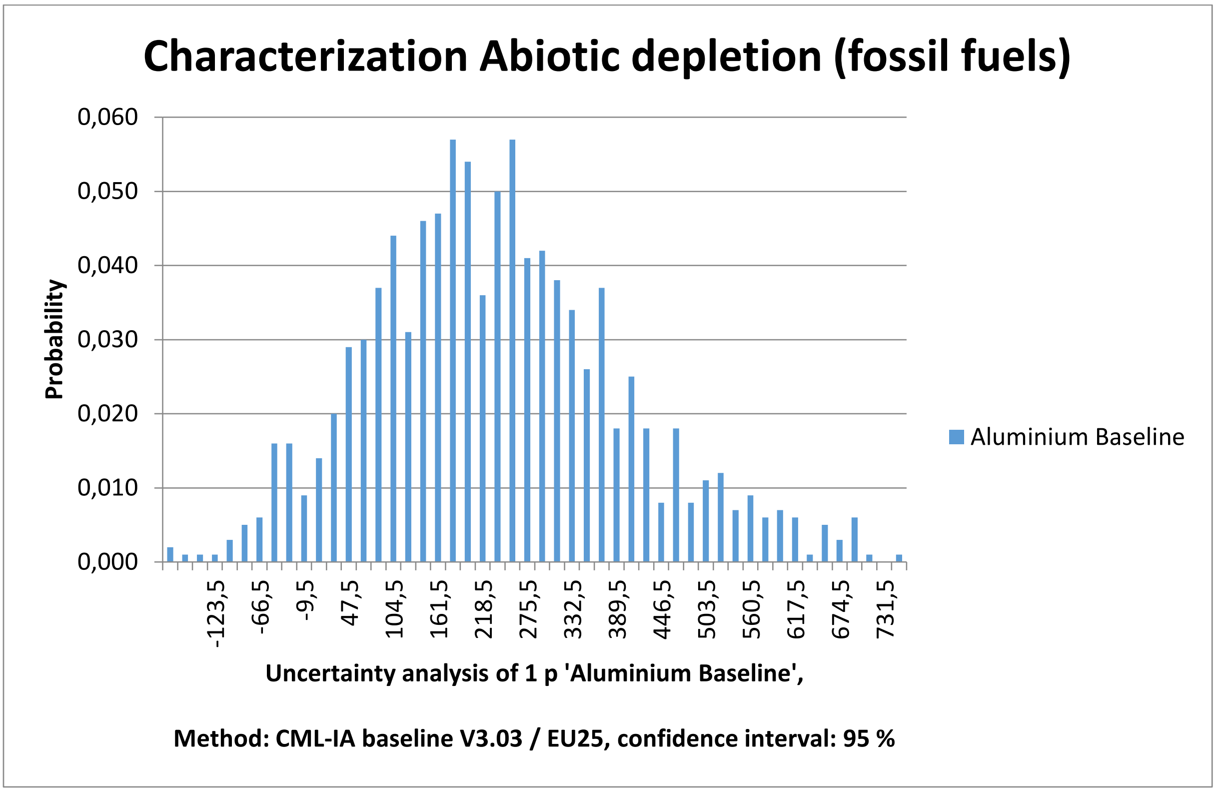

Fig. 43: Uncertainty analysis for aluminium baseline with pedigree matrix. Indicator: abiotic depletion of fossil fuels.

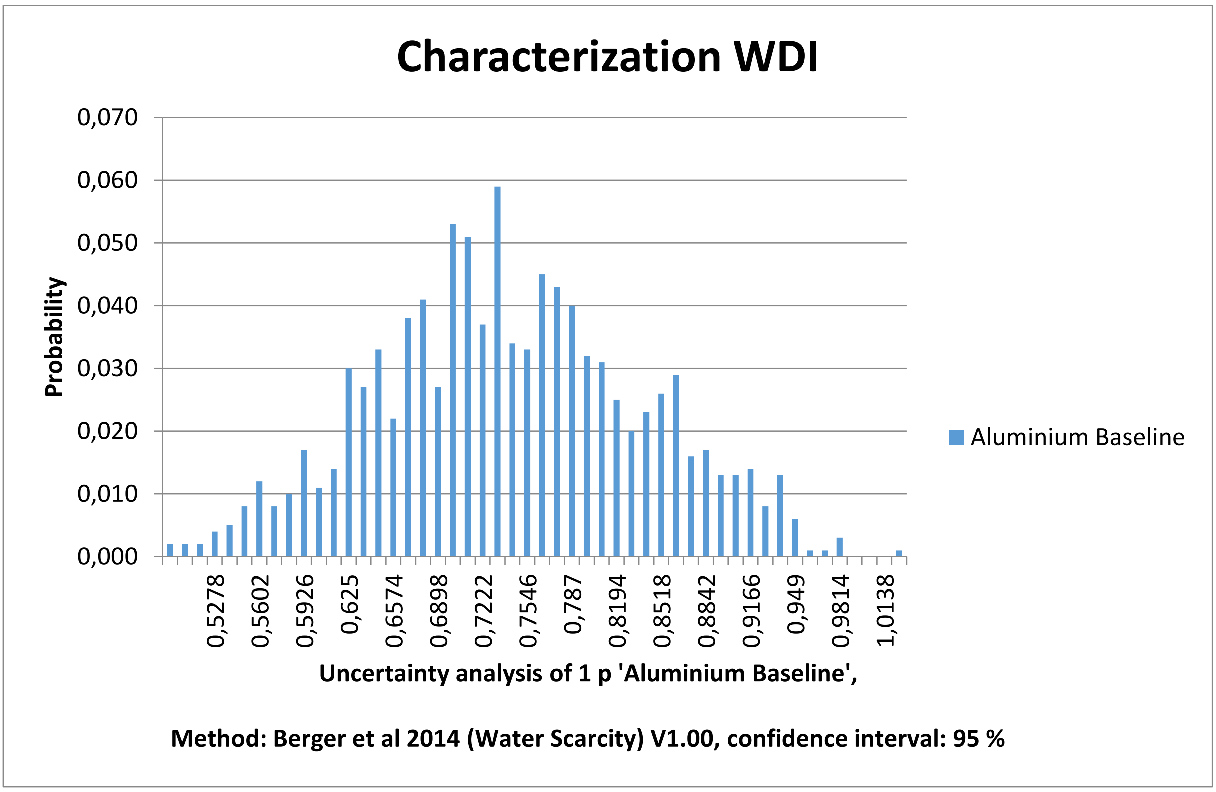

Fig. 44: Uncertainty analysis for aluminium baseline with pedigree matrix. Indicator: water footprint.

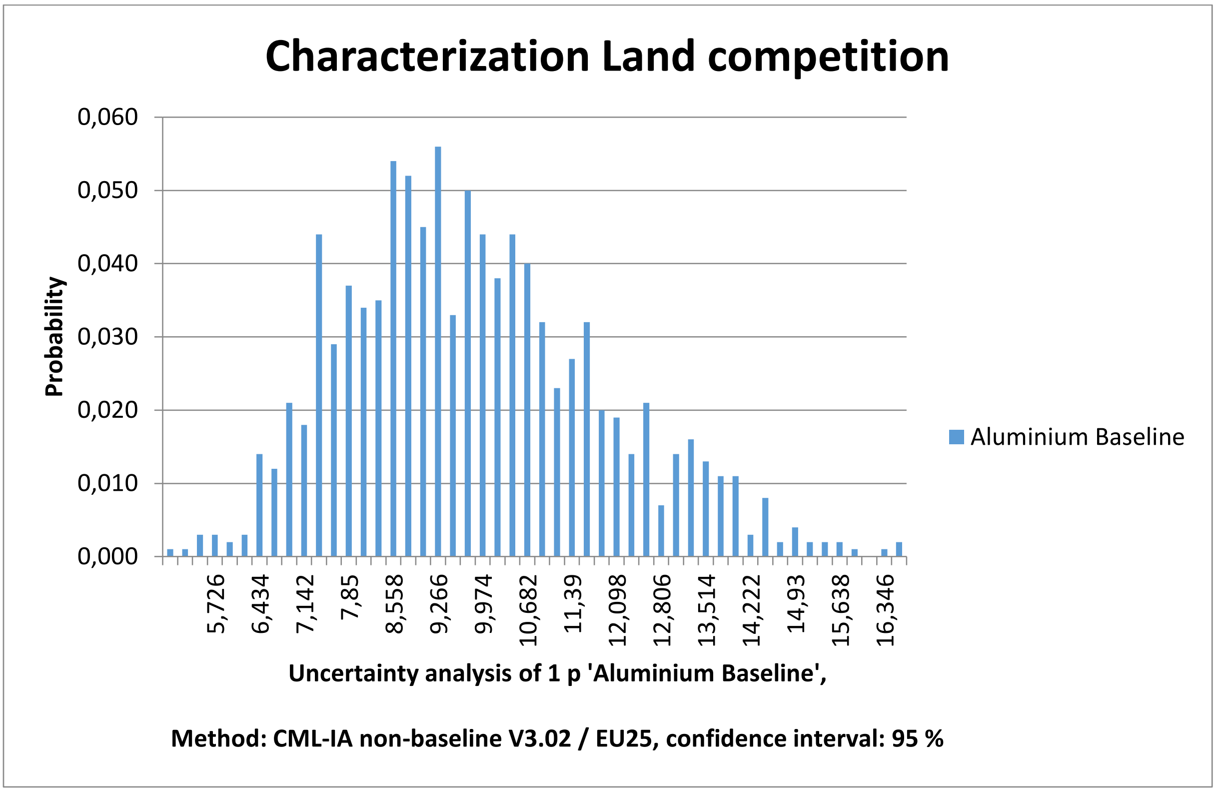

Fig. 45: Uncertainty analysis for aluminium baseline with pedigree matrix. Indicator: Land competition.

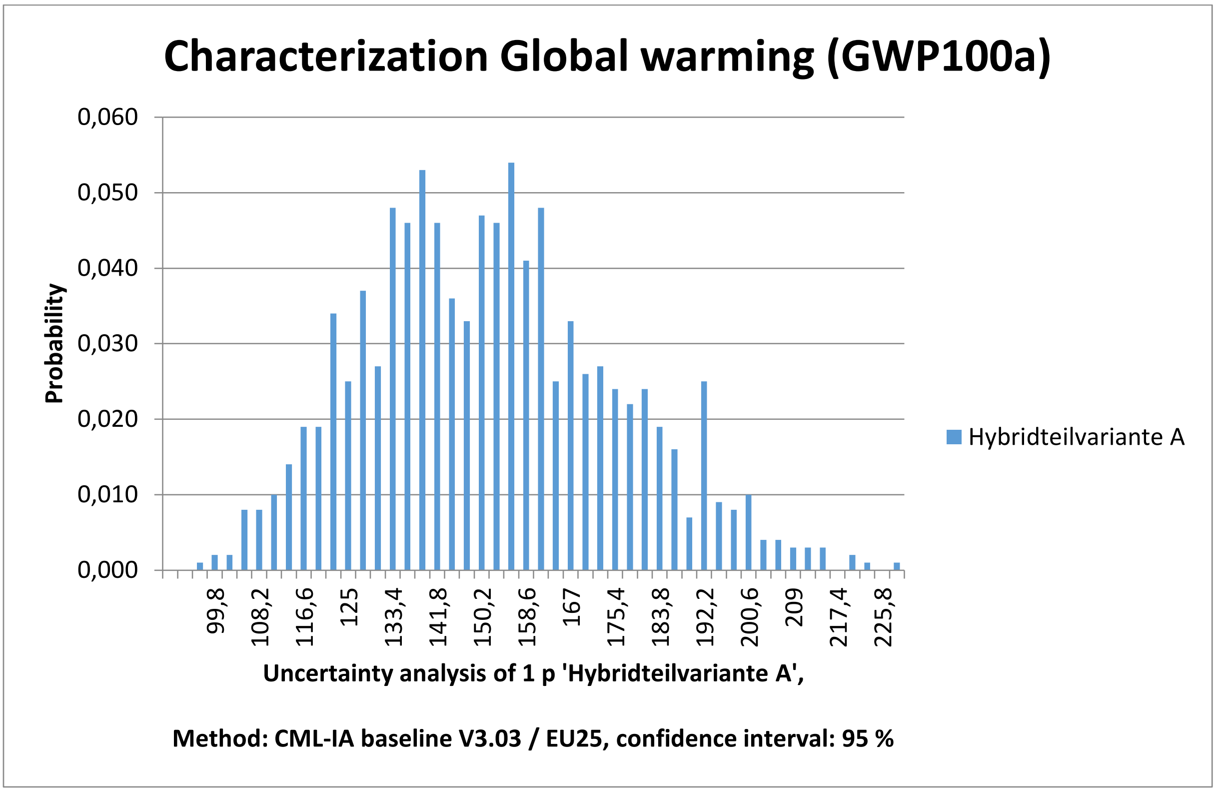

Fig. 46: Uncertainty analysis for hybrid variant A with pedigree matrix. Indicator: global warming potential.

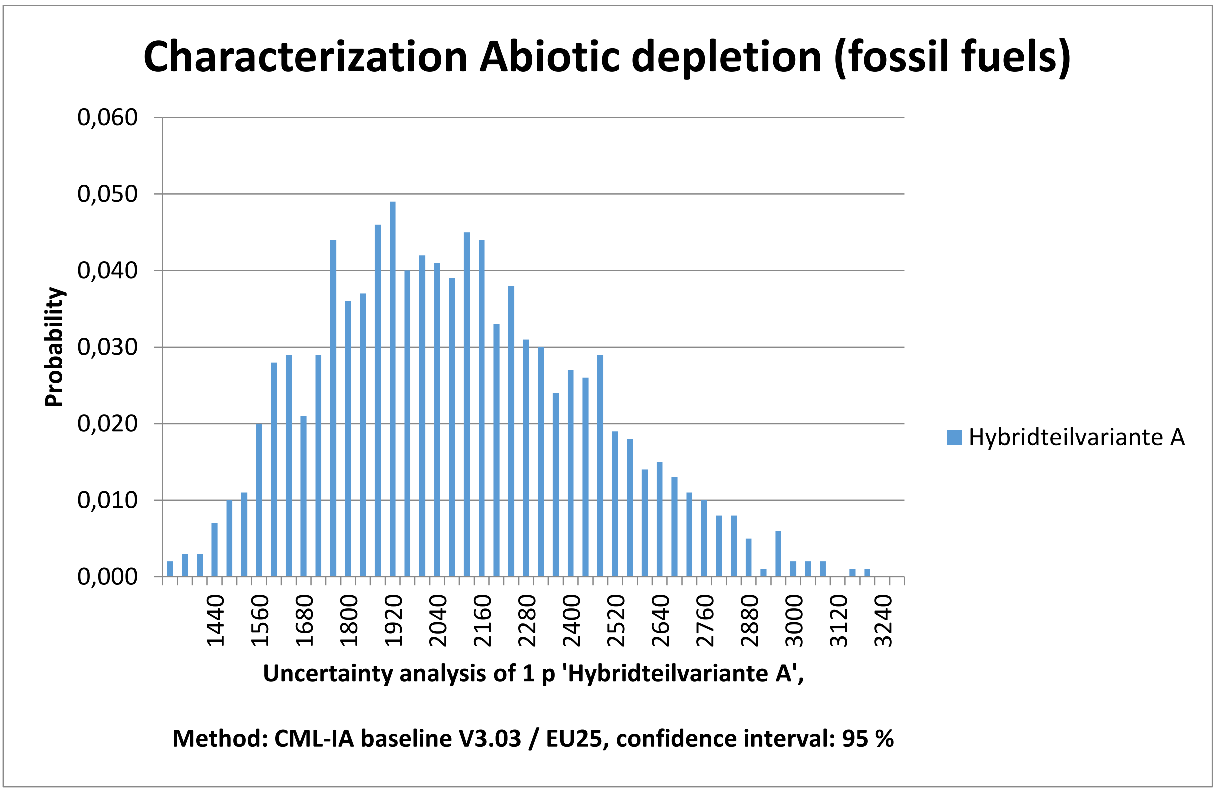

Fig. 47: Uncertainty analysis for hybrid variant A with pedigree matrix. Indicator: abiotic depletion of fossil fuels.

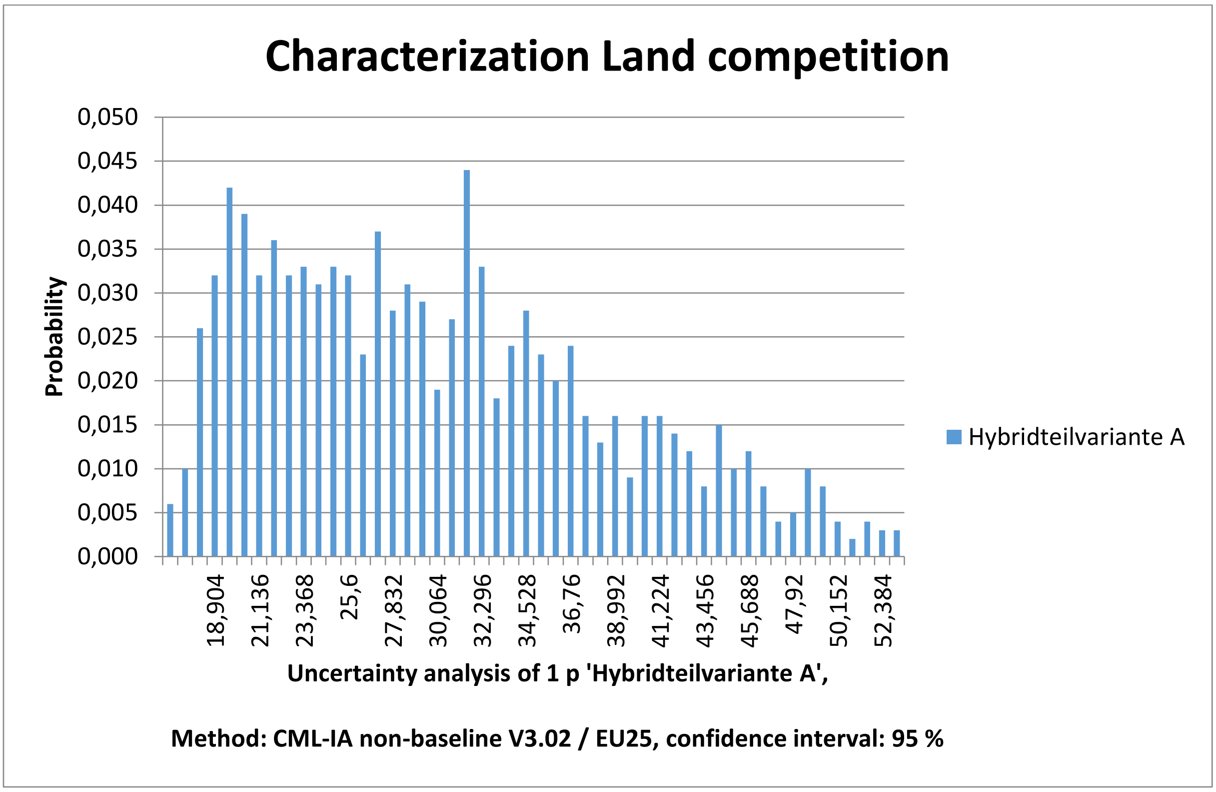

Fig. 48: Uncertainty analysis for hybrid variant A with pedigree matrix. Indicator: land competition.

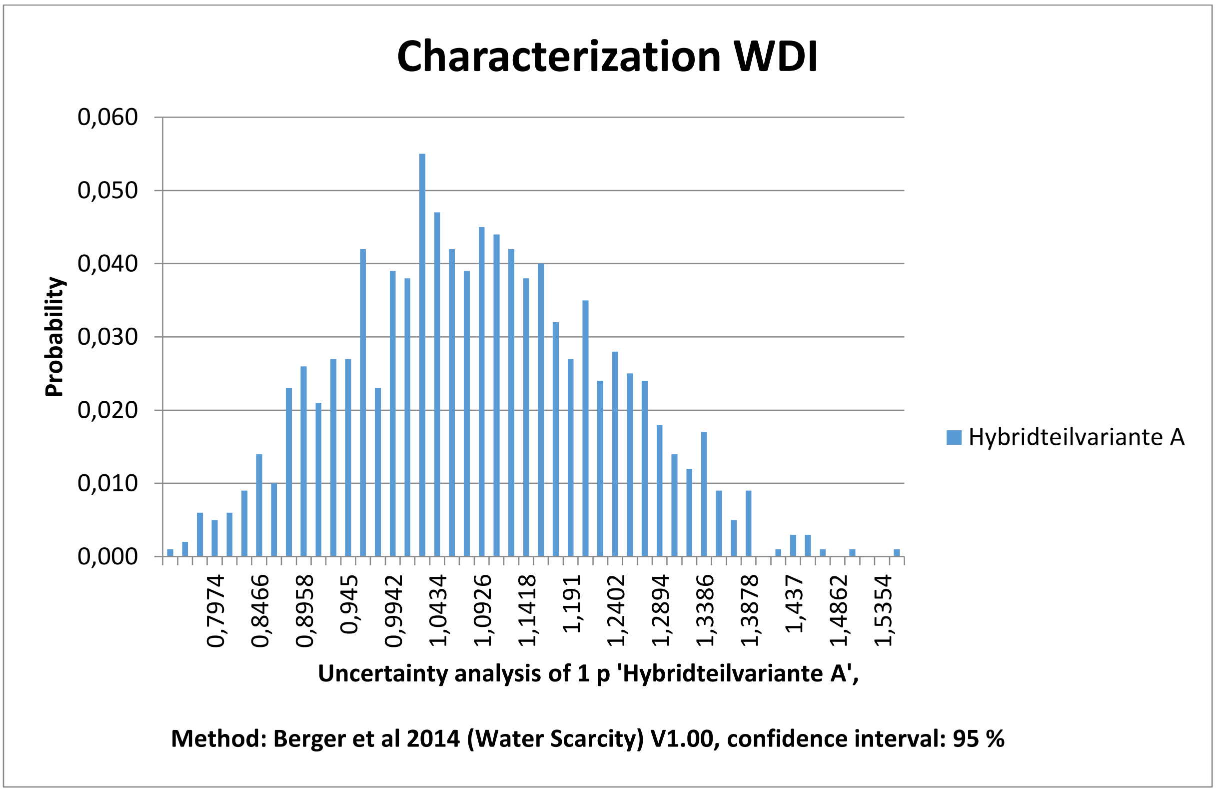

Fig. 49: Uncertainty analysis for hybrid variant A with pedigree matrix. Indicator: water footprint.

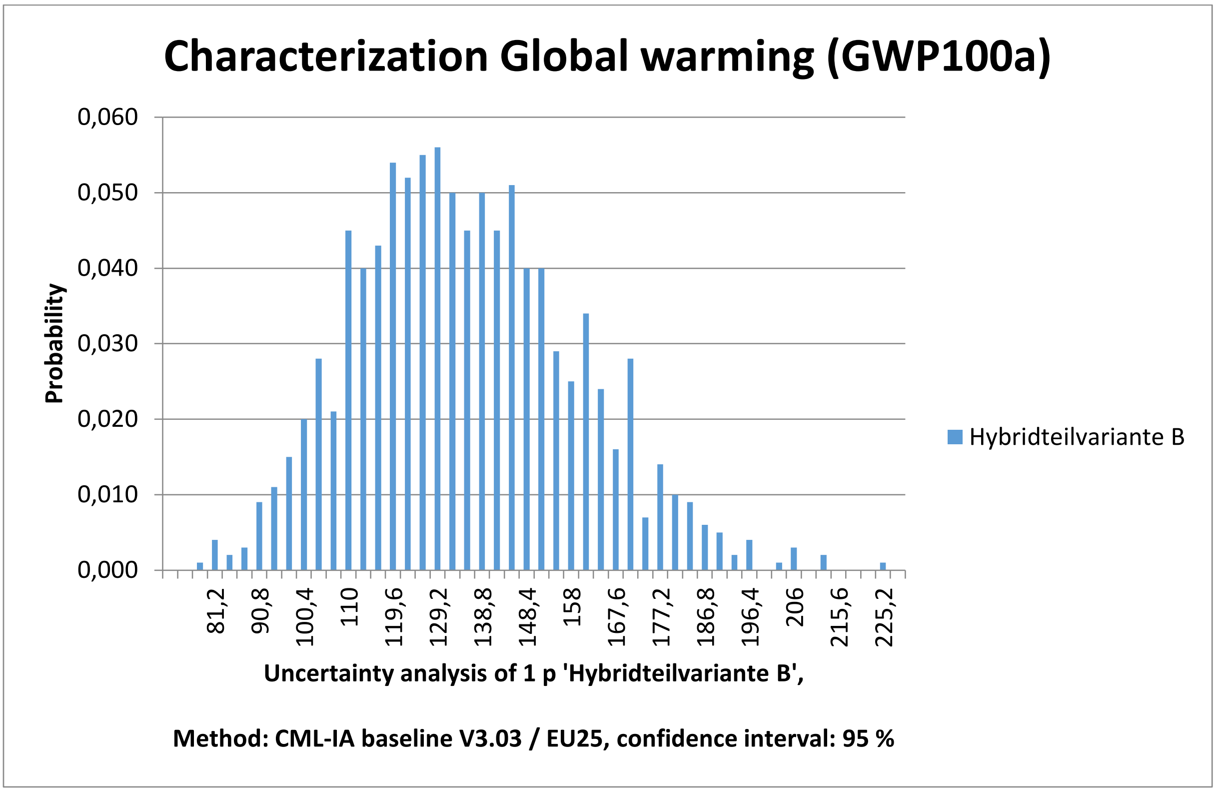

Fig. 50: Uncertainty analysis for hybrid variant B with pedigree matrix. Indicator: global warming potential.

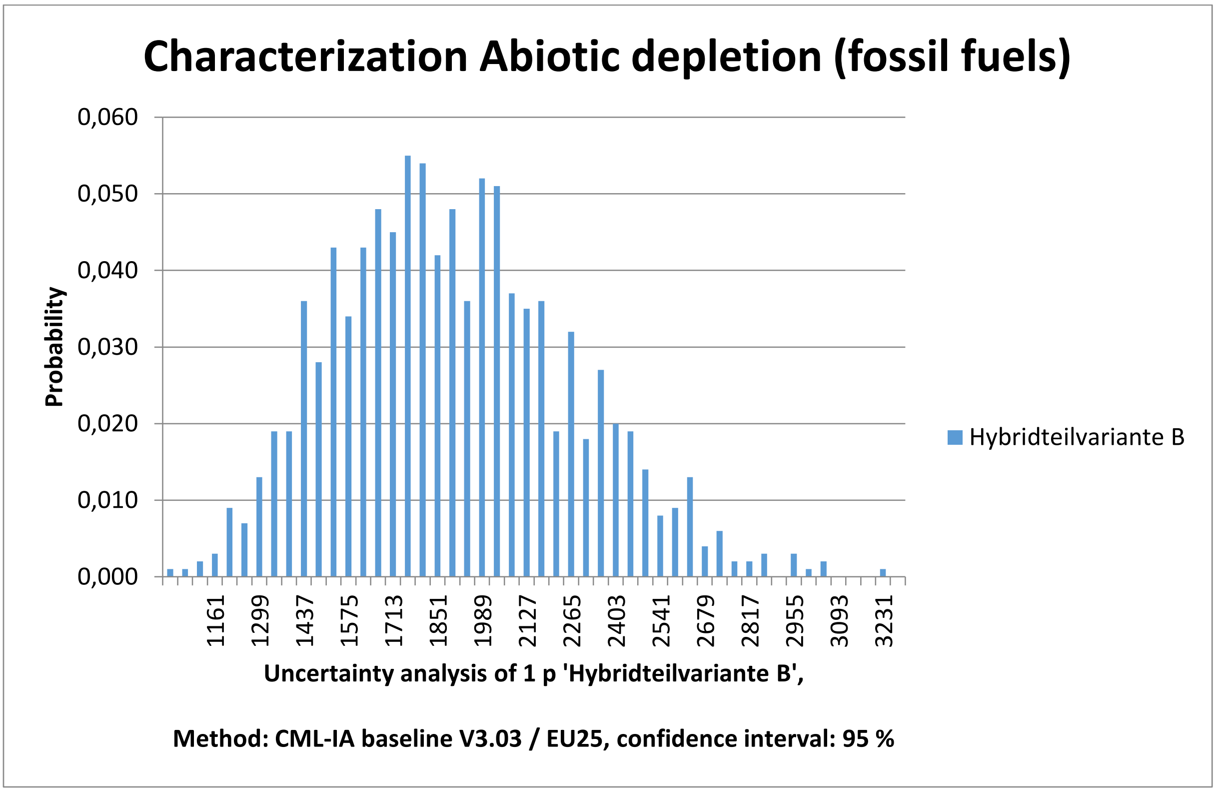

Fig. 51: Uncertainty analysis for hybrid variant B with pedigree matrix. Indicator: abiotic depletion of fossil fuels.

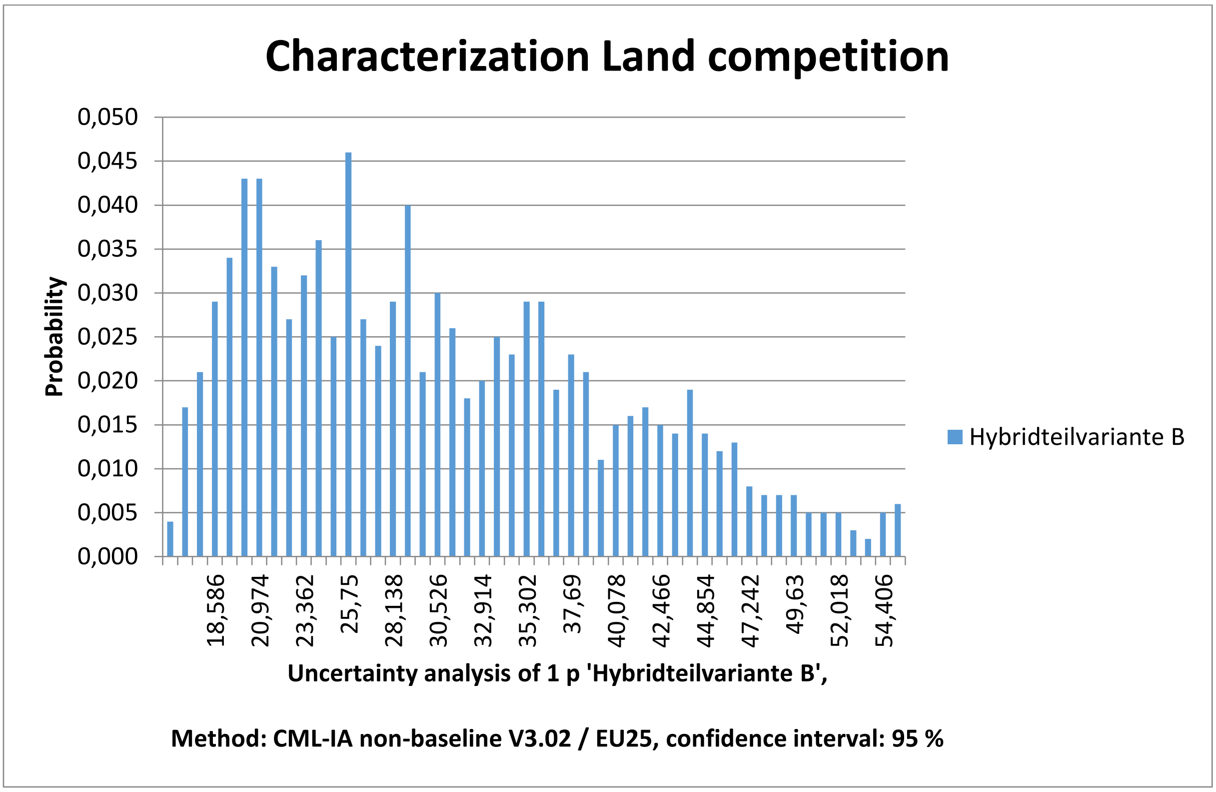

Fig. 52: Uncertainty analysis for hybrid variant B with pedigree matrix. Indicator: land competition.

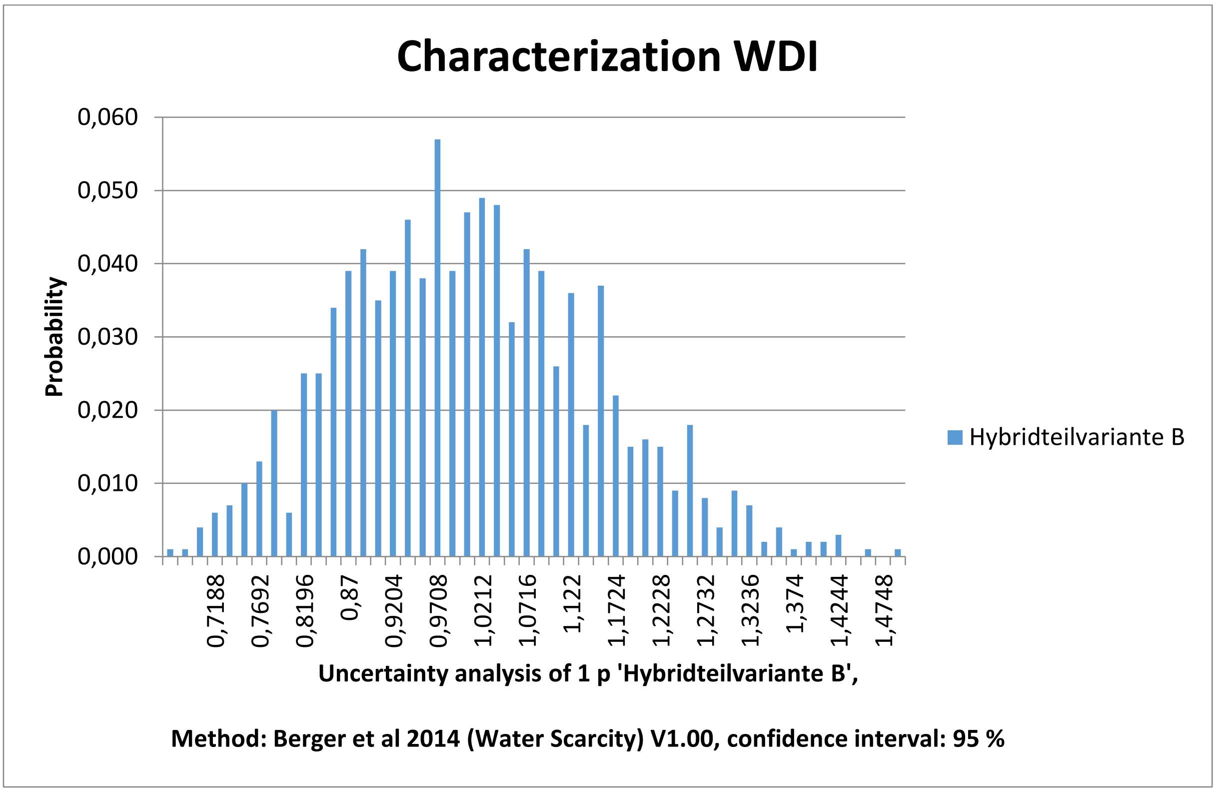

Fig. 53: Uncertainty analysis for hybrid variant B with pedigree matrix. Indicator: water footprint.

In-house expert interviews

This section provides the questions that have been asked within the scope of in-house expert talks. Five interviews have been carried out interviewing eight persons in personal and group interviews regarding the influence of life cycle analysis and their results to corporate decision making. The following persons have been interviewed:

- Ing. Bruno Götzinger, head of advanced technology development / lightweight
- DI Stefan Kaufmann, engineer for composite materials and technologies
- Ing. Bernhard Hofer, project manager alternative vehicle concepts
- Sabine Harmusz, B.A., project manager alternative vehicle concepts
- Ing. Axel-Oscar Bernt, project manager alternative fuel systems / H2
- Alexander Schärfl, Dipl.-Ing. (FH), project manager alternative fuel systems / H2
- Severin Stadler, Dipl.-Ing., software developer
- Ing. Franz Mayr, head of advanced development / innovation and project management

The following questions were asked where applicable:

- Do life cycle assessment results have an influence regarding a product or process-related decision?
- In what way does Magna Steyr incorporate results from life cycle assessments?
- At which position on the decision cascade are life cycle results situated?
- Which impact do LCA results have in the development?
    - Are material choices critically analyzed?
    - Do results lead to sensitisation?
- Is there a point in the Magna Steyr Development System at which the production of an LCA is required?
- Does LCA only represent an image product or do they produce valuable information?
- Is there any coordination with the environmental department if there is more than one material concept available?
- Do LCAs have an impact in a feasibility phase or are material concepts stipulated by the customer only?

- Placement of results: in what way must vertical communication be improved to lead to a better standing within the corporate organization?
- Should a project finish require LCAs to be carried out?
- Does the OEM or client ask for LCA results?
- Presentation of LCAs: do they require a parameter, characteristic, benchmark or performance indicator to enable quick and easy comparison to other products?
- Does an LCA produce a basis for discussion?
- How does LCA go along with social responsability: can an LCA influence a material choice supporting deliberate environmental-friendly suppliers?

Appendix/Annex

Life cycle inventory data

This next section provides detailed information about the life cycle inventory. All processes and material datasets have been appended here. This section is divided into the overall assembly, meaning the single components of each material scenario. The other part represents the actual datasets which have been exported from SimaPro 8.2.

Assembly Inventory:

Category type	Assembly		Distribution	SD	Min	Max
Products						
Alu-Blech	1	p	Dachquertraeger\Bauteile			
Materials/assemblies						
Aluminium sheet	2,7	kg	Undefined			

Category type	Disposal scenario		
Products			
Aluminium Baseline	1	p	Dachquertraeger
Reference assembly			
Aluminium Baseline	1	p	Undefined
Waste scenarios			
EOL Recycling	100	%	Undefined

Category type	Life cycle		
Products			
Aluminium Baseline	1	p	Dachquertraeger
Assembly			
Aluminium Baseline	1	p	Undefined
Waste/Disposal scenario			
EOL Recycling			Undefined

Category type	Assembly		
Products			
Aluminium Baseline	1	p	Dachquertraeger

Materials/assemblies					
GussBT_Untere Schale	1	p	Undefined		
GussBT_Obere Schale	1	p	Undefined		
GussBT_Gussteil	1	p	Undefined		
Klappenscharnier	2	p	Undefined		
Processes					
Spot welding	12	p	Undefined		
Automotive Anticorrosion + Painting	2,54	m2	Undefined		
Transport, freight, lorry >32 metric ton, EURO5 {GLO}| market for | Alloc Def, S	23,8	tkm	Undefined		

Category type	Assembly				
Products					
GussBT_Gussteil	1	p	Dachquertraeger\Bauteile		
Materials/assemblies					
Aluminium cast	4,89	kg	Undefined		
Processes					
Transport, freight, lorry >32 metric ton, EURO6 {GLO}| market for | Alloc Def, S	2,0293	tkm	Triangle	1,907	2,1516

Category type	Assembly				
Products					
GussBT_Gussteil for baseline components	1	p	Dachquertraeger\Bauteile		
Materials/assemblies					
Aluminium cast for baseline components	4,89	kg	Undefined		
Processes					
Transport, freight, lorry >32 metric ton, EURO6 {GLO}| market for | Alloc Def, S	2,0293	tkm	Triangle	1,907	2,1516

Category type	Assembly				
Products					
GussBT_Obere Schale	1	p	Dachquertraeger\Bauteile		
Materials/assemblies					
Aluminium sheet	1,4	kg	Undefined		
Processes					
Transport, freight, lorry >32 metric ton, EURO6 {GLO}| market for | Alloc Def, S	0,406	tkm	Triangle	0,392	0,42

Category type	Assembly				
Products					
GussBT_Untere Schale	1	p	Dachquertraeger\Bauteile		
Materials/assemblies					
Aluminium sheet	0,73	kg	Undefined		
Processes					
Transport, freight, lorry >32 metric ton, EURO6 {GLO}| market for | Alloc Def, S	0,02117	tkm	Triangle	0,02044	0,0219

Category type	Assembly				
Products					
HTV_A Preform	1	p	Dachquertraeger\Bauteile		
Materials/assemblies					
Menzolit C-SMC Preform Production	2,74	kg	Undefined		
Adhesive Film	0,6	kg	Undefined		
Processes					
Transport, freight, lorry >32 metric ton, EURO6 {GLO}| market for | Alloc Def, S	3,451	tkm	Triangle	3,23	3,62

Category type	Assembly				
Products					
HTV_B	1	p	Dachquertraeger\Bauteile		
Materials/assemblies					
Adhesive Film	0,6	kg	Undefined		
Processes					
HTV_B_smc_rec_pressen_Teil	1	p	Undefined		

Category type	Assembly				
Products					
HTV_B_Preform	1	p	Dachquertraeger\Bauteile		
Materials/assemblies					
Recycled SMC	1,21	kg	Undefined		
Laminate CFRP Preform Production	1,76	kg	Undefined		
Adhesive Film	0,6	kg	Undefined		
Processes					
Transport, freight, lorry >32 metric ton, EURO6 {GLO}| market for | Alloc Def, S	1,3923	tkm	Triangle	1,3209	1,4637

Category type	Assembly				
Products					
Hybridteilvariante A	1	p	Dachquertraeger		
Materials/assemblies					
HTV_A Preform	1	p	Undefined		
Alu-Blech	1	p	Undefined		
Klappenscharnier	2	p	Undefined		
Processes					
Automotive Anticorrosion + Painting	0,99	m2	Undefined		
HTV_A_smc_pressen_Teil	1	p	Undefined		
Transport, freight, lorry >32 metric ton, EURO6 {GLO}| market for | Alloc Def, S	2,3556	tkm	Triangle	2,2348	2,4764

Category type	Assembly				
Products					
Hybridteilvariante B	1	p	Dachquertraeger		
Materials/assemblies					
HTV_B_Preform	1	p	Undefined		
Alu-Blech	1	p	Undefined		
Klappenscharnier	2	p	Undefined		
Processes					
Automotive Anticorrosion + Painting	0,99	m2	Undefined		
HTV_B_smc_rec_pressen_Teil	1	p	Undefined		
Transport, freight, lorry >32 metric ton, EURO6 {GLO}| market for | Alloc Def, S	2,4453	tkm	Triangle	2,3199	2,5707

Category type	Assembly				
Products					
Klappenscharnier	1	p	Dachquertraeger\Bauteile		
Materials/assemblies					
Aluminium, primary, ingot {CA-QC}| production | Alloc Def, S	800	g	Undefined		
Processes					
Aluminium removed by drilling, computer numerical controlled {RER}| aluminium drilling, computer numerical controlled | Alloc Def, S	150	g	Undefined		
Aluminium removed by turning, average, computer numerical controlled {RER}| aluminium turning, average, computer numerical controlled | Alloc Def, S	50	g	Undefined		
Welding, arc, aluminium {GLO}| market for | Alloc Def, S	0,25	m	Undefined		
Transport, freight, lorry >32 metric ton, EURO6 {GLO}| market for | Alloc Def, S	0,31	tkm	Triangle	0,3	0,32

Process inventory:

Process	Amount	Unit	Distribution	SD	Min	Max
Products						
Adhesive Film	1	kg	100	not defined	Chemicals	
Avoided products						
Resources						
Materials/fuels						
Polystyrene, general purpose {RER}| production | Alloc Def, S	250	g	Lognormal	1,08		
Limestone, crushed, washed {GLO}| market for | Alloc Def, S	250	g	Lognormal	1,08		
Bisphenol A epoxy based vinyl ester resin {RER}| production | Alloc Def, S	50	g	Lognormal	1,07		
Formaldehyde {RER}| oxidation of methanol | Alloc Def, S	250	g	Lognormal	1,08		
Dummy_Silicone dioxide, at plant/kg/RNA	50	g	Lognormal	1,08		
Dummy for Adhesive Film	150	g	Lognormal	1,08		
Electricity/heat						
Electricity, low voltage {AT}| market for | Alloc Def, S	1	kWh	Lognormal	1,16		

Process						
Category type	Material					
Process identifier	MagSteyr000036994900015					
Infrastructure	No					
Date	10.10.2016					
Products						
Aluminium cast	1	kg	100	Aluminium	Metals	
Avoided products						
Resources						
Materials/fuels						
Aluminium, primary, cast alloy slab from continuous casting {CA-QC}| production | Alloc Def, S	2	kg	Undef.			
Aluminium removed by drilling, computer numerical controlled {RER}| aluminium drilling, computer numerical controlled | Alloc Def, S	0,1	kg	Lognormal	1,19		

Degreasing, metal part in alkaline bath {RER}| processing | Alloc Def, S	5	m2	Lognormal	1,14		
Cast iron removed by milling, large parts {RER}| cast iron milling, large parts | Alloc Def, S	0,5	kg	Lognormal	1,1		
Electricity/heat						
Heat, district or industrial, natural gas {GLO}| market group for | Alloc Def, S	0,7	kWh	Triangle		0,5	2
Transport, freight, lorry >32 metric ton, EURO6 {GLO}| market for | Alloc Def, S	0,105	tkm	Triangle		0,1	0,11
Waste to treatment						
Aluminium (waste treatment) {GLO}| recycling of aluminium | Alloc Def, S	0	kg	Undef.			

Process						
Category type	Material					
Process identifier	MagSteyr000036994900016					
Date	10.10.2016					
Products						
Aluminium sheet	1	kg	100	Aluminium	Metals	
Avoided products						
Resources						
Materials/fuels						
Aluminium, primary, ingot {CA-QC}| production | Alloc Def, S	2,5	kg	Undef.			
Aluminium removed by drilling, computer numerical controlled {RER}| aluminium drilling, computer numerical controlled | Alloc Def, S	0,1	kg	Lognormal	1,13		
Impact extrusion of aluminium, 3 strokes {RER}| processing | Alloc Def, S	1	kg	Lognormal	1,08		
Electricity/heat						
Degreasing, metal part in alkaline bath {RER}| processing | Alloc Def, S	1,27	m2	Undef.			
Electricity, medium voltage {AT}| market for | Alloc Def, S	1,57	kWh	Triangle		1	3
Transport, freight, lorry >32 metric ton, EURO6 {GLO}| market for | Alloc Def, S	0,31	tkm	Triangle		0,3	0,32
Waste to treatment						

Aluminium (waste treatment) {GLO}| recycling of aluminium | Alloc Def, S		0	kg	Undef.			

Process							
Category type	Processing						
Process identifier	MagSteyr000036994900045						
Date	21.10.2016						
Generator	Henning Sommer based on exchange - Dietmar Hofer / Andreas Schiffleitner						
Products							
Automotive Anticorrosion + Painting		1	m2		100	not defined	Painting
Avoided products							
Resources							
Materials/fuels							
Dummy_Tinted clearcoat materials, at plant/US		0,00000254	m3	Undef.			
Dummy_Clearcoat material, at plant/US		0,0000168	m3	Undef.			
Dummy_Tinted clearcoat materials, at plant/US		0,00000352	m3	Undef.			
Dummy_Electrocoat resin, at plant/US		0,000031	m3	Undef.			
Process water, ion exchange, production mix, at plant, from groundwater RER S		18	kg	Undef.			
Dummy_Pigment, at plant/kg/RNA		0,00000265	kg	Undef.			
Electricity/heat							
Electricity, medium voltage {AT}| market for | Alloc Def, S		10	kWh	Undef.			
Heat, central or small-scale, natural gas {RER}| market group for | Alloc Def, S		10	kWh	Undef.			
Emissions to air							
VOC, volatile organic compounds	low. pop.		0,0156	kg		Undef.	
Waste to treatment							

Process	
Category type	Material

Process identifier	MagSteyr000036994900008						
Date	23.09.2016						
Generator	Henning Sommer						
Products							
Carbon Fiber		1000	kg	100	Plastics	Textiles	
Avoided products							
Resources							
Oxygen		1540	kg	Undef.			
Materials/fuels							
Nitrogen, liquid {RER}| market for | Alloc Def, S		940	kg	Lognormal	1,05		
Epoxy resin, liquid {RER}| production | Alloc Def, S		10	kg	Triangle		10	100
Water, deionised, from tap water, at user {GLO}| market for | Alloc Def, S		2880	kg	Lognormal	1,05		
Sulfuric acid {RER}| production | Alloc Def, S		20	kg	Lognormal	1,05		
Polyacrylonitrile fibres (PAN), from acrylonitrile and methacrylate, prod. mix, PAN w/o additives EU-27 S		1816	kg	Lognormal	1,05		
Electricity/heat							
Electricity, low voltage {IT}| market for | Alloc Def, S		22850	kWh	Undef.			
Process steam from natural gas, heat plant, consumption mix, at plant, MJ EU-27 S		12850	kWh	Undef.			
Emissions to air							
Hydrogen cyanide	low. pop.	15,7	kg	Log-normal	1,07		
Ethane	low. pop.	0,01	kg	Log-normal	1,08		
Ammonia	low. pop.	1,16	kg	Log-normal	1,08		
Carbon monoxide	low. pop.	3,24	kg	Log-normal	1,09		
Carbon dioxide	low. pop.	1013	kg	Log-normal	1,09		
Nitrogen dioxide	low. pop.	1,4	kg	Log-normal	1,09		
Water	low. pop.	1806	kg	Log-normal	1,09		
Heat, waste	low. pop.	13000	kWh	Log-normal	1,09		
Emissions to water							
Sulfuric acid		19,9	kg	Log-normal	1,09		

Process								
Category type	Waste treatment							
Process identifier	MagSteyr000036994900043							
Date	21.10.2016							
Waste treatment								
CFRP Recycling by pyrolysis		1	kg	All waste types	Plastics			
Avoided products								
Carbon Fiber		0,42	kg	Undef.				
Resources								
Materials/fuels								
Transport, freight, lorry >32 metric ton, EURO6 {GLO}| market for | Alloc Def, S		1,15	tkm	Undef.				
Electricity/heat								
Electricity, for reuse in municipal waste incineration only {DE}| market for | Alloc Def, S		15	kWh	Triangle			0	50

Process						
Category type	Material					
Process identifier	MagSteyr000036994900013					
Date	10.10.2016					
Products						
Compound		480	kg	100	Others	Chemicals
Avoided products						
Resources						
Materials/fuels						
Dummy_Hydrogen peroxide/kg/RNA		5	kg	Undef.		
Dummy_Additives		15	kg	Undef.		
Dummy_Inhibitors		2	kg	Undef.		
Calcium carbonate > 63 microns, production, at plant EU-27 S		53	kg	Undef.		
Dummy_Zinc stearate, at plant/US		15	kg	Undef.		
Magnesium oxide {GLO}| market for | Alloc Def, S		10	kg	Undef.		

Epoxy resin, liquid {RER}| production | Alloc Def, S	330	kg	Undef.			
Styrene {RER}| production | Alloc Def, S	50	kg	Undef.			

Process						
Category type	Material					
Process identifier	MagSteyr000036994900053					
Date	06.11.2016					
Products						
Dummy for Adhesive Film		1	kg	100	not defined	Chemicals

Process						
Category type	Material					
Process identifier	MagSteyr000036994900011					
Date	10.10.2016					
Products						
Dummy_Additives		1	kg	100	not defined	Dummy Processes for LCA

Process						
Category type	Material					
Process identifier	MagSteyr000036994900012					
Date	10.10.2016					
Products						
Dummy_Inhibitors		1	kg	100	not defined	Dummy Processes for LCA

Process	
Category type	Waste scenario
Process identifier	MagSteyr000036994900040
Date	13.10.2016
Waste scenario	

EOL Hybrid Recylcing		1	kg		All waste types	Recycling
Materials/fuels						
Electricity/heat						
Electricity, medium voltage {AT}| market for | Alloc Def, S		0,785	kWh		Undef.	
Separated waste						
Al/CFK Hybrid Separation	Others			100		
CFRP Recycling by pyrolysis	Plastics			100		
Aluminium (waste treatment) {GLO}| recycling of aluminium | Alloc Def, S	Aluminium			95		
Remaining waste						
CFRP Recycling by pyrolysis				0		
Waste plastic, mixture {CH}| treatment of, municipal incineration | Alloc Def, S				100		

Process						
Category type	Waste scenario					
Process identifier	MagSteyr000036994900046					
Date	28.10.2016					
Waste scenario						
EOL Recycling		1	kg		All waste types	Recycling
Materials/fuels						
Electricity/heat						
Electricity, medium voltage {AT}| market for | Alloc Def, S		0,785	kWh		Undef.	
Transport, freight, lorry >32 metric ton, EURO6 {GLO}| market for | Alloc Def, S		1	tkm		Undef.	
Separated waste						
Aluminium (waste treatment) {GLO}| recycling of aluminium | Alloc Def, S	Aluminium sheet			90		
Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Alloc Def, S	Ferro metals			90		
Aluminium (waste treatment) {GLO}| recycling of aluminium | Alloc Def, S	Aluminium cast			90		
Remaining waste						
DummyWasteTreatment				100		

Process							
Category type	Processing						
Process identifier	MagSteyr000036994900018						
Date	11.10.2016						
Generator	Henning Sommer						
Products							
HTV_A_smc_Pressen		5,44	kg		100	not defined	Bonding
Avoided products							
Resources							
Materials/fuels							
Menzolit C-SMC		2,74	kg	Undef.			
Aluminium sheet		2,7	kg	Undef.			
Adhesive Film		0,6	kg	Undef.			
Electricity/heat							
Electricity, medium voltage {CZ}| market for | Alloc Def, S		50	kWh	Undef.			

Process							
Category type	Processing						
Process identifier	MagSteyr000036994900029						
Date	13.10.2016						
Generator	Henning Sommer						
Products							
HTV_A_smc_pressen_Teil		1	p		100	not defined	Bonding
Avoided products							
Resources							
Materials/fuels							
Electricity/heat							
Electricity, medium voltage {CZ}| market for | Alloc Def, S		50	kWh	Undef.			

Process	
Category type	Processing
Process identifier	MagSteyr000036994900019
Date	11.10.2016

Generator	Henning Sommer					
Products						
HTV_B_smc_rec_Pressen		5,67	kg	100	not defined	Bonding
Avoided products						
Resources						
Materials/fuels						
Aluminium sheet		2,7	kg	Undef.		
Adhesive Film		0,6	kg	Undef.		
Recycled SMC		1,21	kg	Undef.		
Laminate CFRP		1,76	kg	Undef.		
Electricity/heat						
Electricity, medium voltage {CZ}| market for | Alloc Def, S		50	kWh	Undef.		

Process						
Category type	Processing					
Process identifier	MagSteyr000036994900030					
Infrastructure	No					
Date	13.10.2016					
Generator	Henning Sommer					
Products						
HTV_B_smc_rec_pressen_Teil		1	p	100	not defined	Bonding
Avoided products						
Resources						
Materials/fuels						
Electricity/heat						
Electricity, medium voltage {CZ}| market for | Alloc Def, S		50	kWh	Undef.		

Process						
Category type	Material					
Process identifier	MagSteyr000036994900020					
Date	11.10.2016					
Products						
Laminate CFRP		1	kg	100	Plastics	Plastics\ Thermos.

Avoided products							
Resources							
Materials/fuels							
Carbon Fiber	0,64	kg	Lognormal		1,07		
Epoxy resin, liquid {RER}| production | Alloc Def, S	0,412	kg	Triangle			0,3	0,5
Diethanolamine {RER}| ethanolamine production | Alloc Def, S	0,12	kg	Lognormal		1,07		
Electricity/heat							
Electricity, medium voltage {US}| market group for | Alloc Def, S	2	kWh	Triangle			1,5	2,5
Al/CFK Hybrid Separation	0,021	kg	Undef.				

Process							
Category type	Material						
Process identifier	MagSteyr000036994900038						
Date	13.10.2016						
Products							
Laminate CFRP Preform Production	1,76	kg		100	Plastics	Plastics\ Thermos.	
Avoided products							
Resources							
Materials/fuels							
Laminate CFRP	3,52	kg	Undef.				
Epoxy resin, liquid {RER}| production | Alloc Def, S	0,3	kg	Triangle			0,2	0,4
Electricity/heat							
Electricity, medium voltage {AT}| market for | Alloc Def, S	63	kWh	Triangle			50	70

Process							
Category type	Material						
Process identifier	MagSteyr000036994900042						
Date	11.10.2016						
Products							
Laminate CFRP_reuse	1	kg		100	Plastics	Plastics\ Thermos.	
Avoided products							
Resources							
Materials/fuels							

Laminate CFRP	1	kg	Lognormal		1,09		
Waste to treatment							
Al/CFK Hybrid Separation	0,021	kg	Lognormal		1,1		

Process							
Category type	Material						
Process identifier	MagSteyr000036994900007						
Type							
Date	12.09.2016						
Generator	Henning Sommer						
Collection method	Process information sheet + VDI assessment sheet from Menzolit						
Products							
Menzolit C-SMC	1000	kg		100	Plastics	Plastics\ Thermos.	
Avoided products							
Resources							
Materials/fuels							
Bisphenol A epoxy based vinyl ester resin {RER}| production | Alloc Def, S	330	kg	Triangle			310	350
Calcium carbonate > 63 microns, production, at plant EU-27 S	53	kg	Triangle			45	60
Magnesium oxide {RER}| production | Alloc Def, S	10	kg	Triangle			7,5	12,5
Styrene {RER}| production | Alloc Def, S	50	kg	Triangle			45	55
Carbon Fiber	520	kg	Triangle			500	540
Dummy_Inhibitors	2	kg	Triangle			1	3
Dummy_Additives	15	kg	Triangle			12,5	17,5
Dummy_Zinc stearate, at plant/US	15	kg	Triangle			12,5	17,5
Dummy_Hydrogen peroxide/kg/RNA	5	kg	Triangle			4	6
Electricity/heat							
Electricity, medium voltage {IT}| market for | Alloc Def, S	100	kWh	Triangle			90	110
Waste, hazardous (wfd)/RER	20	kg	Lognormal		1,05		
Waste incineration of plastics (Unspec.) fraction in municipal solid waste (MSW) EU-27 S	5	kg	Lognormal		1,05		

Process	

Category type	Material							
Process identifier	MagSteyr000036994900036							
Date	13.10.2016							
Products								
Menzolit C-SMC Preform Production		2,74	kg		100	Plastics	Plastics\ Thermos.	
Avoided products								
Resources								
Materials/fuels								
Menzolit C-SMC		5,48	kg	Undef.				
Bisphenol A epoxy based vinyl ester resin {RER}| production | Alloc Def, S		0,3	kg	Lognormal		1,05		
Electricity/heat								
Electricity, medium voltage {AT}| market for | Alloc Def, S		63	kWh	Triangle			50	70
Waste incineration of plastics (Unspec.) fraction in municipal solid waste (MSW) EU-27 S		2,74	kg	Undef.				

Process								
Category type	Material							
Process identifier	MagSteyr000036994900021							
Date	11.10.2016							
Products								
Recycled SMC		1000	kg		100	Plastics	Plastics\ Thermos.	
Avoided products								
Laminate CFRP_reuse		1000	kg	Undef.				
Resources								
Materials/fuels								
Laminate CFRP_reuse		1000	kg	Triangle			1000	1040
Bisphenol A epoxy based vinyl ester resin {RER}| production | Alloc Def, S		33	kg	Triangle			20	50
Electricity/heat								
Electricity, medium voltage {IT}| market for | Alloc Def, S		10	kWh	Triangle			10	75

Process

Category type	Material								
Process identifier	MagSteyr000036994900039								
Date	13.10.2016								
Products									
Recycled SMC Preform		1	p		100	not defined	Plastics\ Thermos.		
Avoided products									
Resources									
Materials/fuels									
Bisphenol A epoxy based vinyl ester resin {RER}| production | Alloc Def, S		0,726	kg	Undef.					
Recycled SMC		2,42	kg	Undef.					
Electricity/heat									
Electricity, medium voltage {AT}| market for | Alloc Def, S		63	kWh	Triangle				50	70
Injection moulding {RER}| processing | Alloc Def, S		2,42	kg	Undef.					

Process							
Category type	Processing						
Process identifier	MagSteyr000036994900044						
Date	21.10.2016						
Generator	Henning Sommer based on MSE/MSF data from D. Hofer/BMW X3						
Products							
Spot welding		1	p		100	not defined	Metals\ Welding
Avoided products							
Resources							
Materials/fuels							
Electricity/heat							
Electricity, medium voltage {AT}| market for | Alloc Def, S		0,00278	kWh	Undef.			