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CARBON FOOTPRINT OF PULTRUDED COMPOSITE
PRODUCTS USED IN AUTOMOTIVE APPLICATIONS: CASE
STUDY OF SIDE PANEL OF COACH

Master of Science thesis

ABSTRACT

SAMER ZIADEH: Carbon footprint of pultruded composites products used in automotive applications: case study of side panel of coach
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The growing concern about the climate change is the driving force for several industries to increase their environmental awareness especially for the automotive industry. Carbon footprint (CF) is a method that could be applied to compare products based on their greenhouse gas (GHG) emissions. These gases are the major cause of the climate change and are mostly generated by automobiles. The CO_2 footprint value gives a single clear number which makes it easy to compare products.

The aim of this thesis is to examine the possible and available methods to estimate carbon footprint. For further extensive use of composites, it is critical to estimate the energy consumed and CO_2 footprint emitted during the life time of the composites compared to other conventional materials. This study evaluates the contribution of composite materials in weight reduction which results in energy saving and less environmental impacts. This project is funded with a grant by TUT Foundation.

There is no specific universal definition of the carbon footprint. The PAS 2050 is the only standard established in the United Kingdom. There is an international standard of the CF published by the international Organization for standardization (ISO) called ISO/TS 14067.

Currently, there are several CF labels available in the market. Some of these labels give the carbon footprint values and others show that the product is better than the average. The value is either in grams or kilograms of carbon dioxide equivalent (CO_2e). The global warming potential (GWP) factors are used to quantify the greenhouse gases to CO_2e.

The CF and energy consumption are calculated for the entire life cycle of a side panel of a coach which is manufactured from composite materials and compared with other conventional materials. Different case scenarios of transportation and use phase are analyzed in order to show the potential use of the composite materials over other materials. Further implementations to improve the impacts of composite materials are suggested.

PREFACE

First of all, I would like to thank Professor Jyrki Vuorinen for his support and guidance throughout the thesis work. I would like to thank Exel Composites Company for giving me the opportunity to carry out my research thesis. I would like to express my deep gratitude to Mikko Lassila for being an excellent mentor, great inspiration and for his ultimate support. Special thanks to Kim Sjödahl for his guidance, instructions throughout the thesis. I am also very thankful for everyone associated with the Exel Composites Company, especially Eric Moussiaux for guiding me through the research.

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Also great thanks to all my friends for their support and motivation during my degree years.

"All our dreams can come true if we have the courage to pursue them."

Walt Disney

Tampere, 17.9.2015

Samer Ziadeh

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LIST OF SYMBOLS AND ABBREVIATIONS

BIW	Body in White
BSI	British Standards Institution
CaCO3	Calcium Carbonate
CF	Carbon footprint
CFCs	Chlorofluorocarbons
CFP	Carbon footprint of product
CFRP	Carbon Fiber Reinforced Plastics
CH4	Methane
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
CSM	Chopped Strand Mat
Defra	UK Department for Environment, Food and Rural Affairs
dLUC	direct Land Use Change
EPD	Environmental Product Declaration
ETAP	Environmental Technologies action Plan
EU	European Union
FIFRA	Federal Insecticide, Fungicide and Rodenticide Act
FTC	Federal Trade Commission
GF	Glass Fiber
GFRP	Glass Fiber Reinforced Plastics
GHG	Greenhouse Gases
GMT	Glass Mat Thermoplastics
GWP	Global Warming Potential
HFCs	Hydrofluorocarbons
IPCC	Panel on Climate change
ISO	International Organization for Standardization
JEMAI	Japan Environmental Management Association for Industry
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MJ	Mega Joule
N2O	Nitrous oxide
NF3	Nitrogen trifluoride
NFC	Natural Fiber Composites
NOx	mono-nitrogen oxides
PA	Process Analysis
PAS	Publicly Available Specification
PCR	Product Category Rules
PFCs	Perfluorocarbons
PLA	Polylactic Acid
SETAC	Society of Environmental Toxicology and Chemistry
SF6	Sulphur hexafluoride
SMC	Sheet moulding compounds
TC	Technical Committee
TUT	Tampere University of Technology
U.S.	United States
UD	Unidirectional

UK	United Kingdom
UP	Unsaturated Polyester
WBCSD	World Business council for Sustainable Development
WG	Working Group
WRI	World Resources Institute
WT	Weight
WWF	World Wide Fund for Nature

1. INTRODUCTION

Nowadays the global climate change is considered to be one of the most significant environmental threats and main concern of the world population and governments. Due to several anticipated effects of the global warming comprising increasing temperatures, rising sea levels, melting of the snow and glaciers, droughts and flooding which could definitely leads to loss of land, crops and water supply. The rising of greenhouse gas emissions (GHG) are believed to be the main reason behind the global warming, which are generated either by human activities, such as the consumption of fossil fuels, or by industrial activities. Therefore, reducing the concentrations of greenhouse gas emissions is the solution to prevent any further changes in the climate. In order, to mitigate global warming and adapt to the climate changes, establishing a climate policy will be the key. Finland is one of the leading countries in implementing climate policy based on national, European Union (EU) and international level. Finland's aim is to decrease the amount of GHG emissions emitted in the atmosphere by 80–95% by 2050. This means switching to zero-emissions produced by energy and more efficiency in consumption [1] [2].

Carbon footprint (CF) is one of the GHG, as well as a main contributor in causing the climate change. By calculating the CF of a product through its entire life cycle, the greenhouse gas emissions can be indicated [4]. The carbon footprint is usually calculated based on a functional unit, which is an important step to define the product and the amount of use [7]. Hence, CF is a single indicator and a number that will allow the costumers to compare various types of products according to their environmental impacts on climate [3]. Additionally, the companies will be able to make decisions on how to reduce the amount of emissions of their products.

Currently, many industries have increased the level of environmental protection by adapting to several method in reducing the carbon dioxide (CO_2) to mitigate the climate change. In particular, the transportation industry in EU is considered one of the main contributors of GHG emissions that are generated by automobiles [63]. Therefore, the automotive industry's major challenge is to decrease the amount of emissions in the use phase and to improve the vehicle efficiency. There are several approaches to fulfill the requirements such as alternative fuel systems [87], drive train efficiency [88] and weight reduction of the vehicle [64].

Reducing vehicle mass or weight can be achieved by two significant methods: materials substitution and innovative design. The first method is established through replacing conventional materials such as steel with composite materials. They are considered to

be the leading materials for weight reduction and performance in automobile industry. The second method is to optimize the components to accomplish higher performance [82]. Previous studies, have shown that the potential use of glass reinforced polymers would result in 20-30% weight reduction in vehicles [86]. For several decades, the automotive industry has already employed the advantages of using the composite materials in lower performance applications.

Life Cycle Assessment (LCA) is an assessment methodology established to analyze the environmental impacts of products and services [21] [22]. Many industries, and in particular the automotive industry have implemented the use of LCA. The LCA has been used for standalone assessments of whole vehicles, alternative fuels and materials [89] [87] [65].

1.1 Aim and structure of thesis

The aim of the thesis is to illustrate the availability and used methods to calculate CF and calculate the CF of body parts in the automotive industry. The study case is a side panel of a coach and the calculations of CF are conducted by using the CES Selector software (Eco Audit Tool). Additionally, the significance of using the lightweight materials in automobile applications are highlighted and compared to other conventional materials. This project is funded with a grant by TUT Foundation.

The side panel of a coach used in this study is made of glass fiber reinforced plastics GFRP with a composition of 43.2 wt. % (percentage by weight) of glass fiber and unsaturated polyester resin. The body component is manufactured by pultrusion process. This process is considered the most cost and energy efficient process among other composites processes, due to high rate of production and automation. In this study, the pultruded products of Exel Composites Company are used as a reference [83].

In chapter two, carbon footprint is explained as well as several definitions of CF are provided. International Organization for Standardization (ISO) has finally defined the carbon footprint as a sum of GHG emissions and removals in a product system which is expressed as CO_2 equivalents. Moreover, two different approaches are described to calculate the CF of a product. The first approach is bottom-up method. The product is modeled, by involving several processes and connecting them to material and energy flows. The second approach is top-down; the product life cycle stages are divided and evaluated based on each stage cost. The GHG emissions are estimated after establishing the correlation between the cost statistics and environmental effects in each stage.

Furthermore, three standards on the carbon footprint are described in chapter two. PAS 2050 standard is published by BSI in United Kingdom which defines a method on how to calculate GHG emissions of a product life cycle. The ISO-14067 standard objectives are divide into two parts: measuring the CF and communicating with customers (e.g.

Labels). The final standard is the GHG Protocol: A Corporate Accounting and Reporting Standard which describes an accounting tool used generally by organizations to understand, calculate and regulate GHG emissions.

Additionally, different types of environmental labels are presented in chapter two. A brief history of the environmental labels and various labels that are available in the market. Also three various categories of labels are described.

The CF calculation is based on a life cycle assessment (LCA). LCA is a method used to estimate the environmental effects of a products entire life cycle. In chapter three, the main phases of the LCA method are characterized. Different types of LCA softwares are reviewed and compared based on several specifications. CES selector by Granta design is used due to the high cost of the most common softwares and limitation of the free databases. The tool Eco Audit is used in this study and the methodology of the tool is explained. Previous studies about life cycle assessment on composites materials are reviewed.

Chapter four focuses on the side panel case. Firstly, the side panel case is described. The composite material used in this study and the other conventional materials are defined. Secondly, the product is modeled by using bottom-up method. The modeling is done by using Eco audit tool in CES selector software [62]. A CES selector is software used for materials design and selection [62]. The life cycle stages of the study included are raw materials extraction, manufacturing, transportation, use of the product and end-of-life. Moreover, the methodology used to analyze and calculate the CF is defined. The data collection of the case is based on the Granta design databases and on information gathered from the manufacture. The basic equations used in the estimation of CF and energy consumption for each stage are explained.

In chapter five the total energy consumed and CO_2 footprint are calculated for the entire life cycle of the stainless steel, aluminium, carbon steel and the composite material. The values are analyzed and compared for each stage of the product life cycle. Two case scenarios of transportation of the product are investigated. Three case scenarios, including diesel, gasoline and electric family car, in the usage phase are examined. Finally, several recommendations are suggested to improve the use of composite materials in automotive applications. The further work of implementing the biocomposites materials and recycling methods would reduce the impacts of using the composite materials in automotive industry.

2. CARBON FOOTPRINT

There is no particular universal definition of carbon footprint and argument continues about the exact meaning of this term, the accurate method to measure it as well as the unit of CF [4]. The carbon footprint concept derives from the Ecological Footprint which had been first raised by Wackernagel and Rees in 1996 [5]. In the Ecological Footprint, there are three approaches in order to convert the consumption of the fossil energy into an equivalent land area. One of these approaches is to measure the land area required to isolate the CO_2 produced from burning fossil fuel in order to estimate the land requirement for energy use [5]. Accordingly, the numbers of the public and political concerns have dramatically increased regarding the climate change. The Carbon footprint has been established into a discrete concept with comprehensive scopes. In the LCA standards ISO 14040 and 14044, the GHG emissions are covered quite well. There are several environmental impact category indicators and one of those indicators is climate change [6]. Carbon footprint can be seen as a simplified and subset process of LCA and has a more visible appeal [3]. Therefore, the main purpose of the carbon footprint is to indicate the product's impact on the climate with one clear number. This makes it easier to understand the value of CF and surpasses the other environmental impacts. There are several definitions of the carbon footprint below in the Table 1.

Table 1. *Different definitions of Carbon footprint [7][8][9].*

Source	Definition of carbon footprint
PAS 2050	"Carbon footprint is a term used to describe the amount of greenhouse gas (GHG) emissions caused by a particular activity or entity, and thus a way for organizations and individuals to assess their contribution to climate change."
Wright, Kemp, and Williams	"A measure of the total amount of carbon dioxide (CO_2) and methane (CH_4) emissions of a defined population, system or activity, considering all relevant sources, sinks and storage within the spatial and temporal boundary of the population, system or activity of interest. Calculated as carbon dioxide equivalent (CO_2e) using the relevant 100-year global warming potential (GWP100)."
Carbon Trust	"A carbon footprint is the total greenhouse gas (GHG) emissions caused directly and indirectly by an individual, organization, event or product, and is expressed as a carbon dioxide equivalent (CO_2e)."

According to recent ISO/TS 14067, the carbon footprint of a product is defined as *"a sum of greenhouse gas emissions and removals in a product system, expressed as CO_2 equivalents and based on a life cycle assessment using impact category of climate change"* [10].

Moreover, the CO_2 equivalence (or CO_2e) is used to express a carbon footprint, which consists of a number of various greenhouse gases in an individual figure. A carbon footprint may comprise a number of categories of greenhouse gases. For instance, all those gases controlled under the Kyoto Protocol [11]. The Kyoto gases are listed in the Table 2 below with their global warming potential (GWP).

Table 2. *Greenhouse gases and Global warming potentials [12].*

Greenhouse gas and chemical formula	Global Warming Potential (GWP) (100 year time horizon)
Carbon dioxide (CO_2)	1
Methane (CH_4)	25
Nitrous oxide (N_2O)	298
Hydrofluorocarbons (HFCs)	140–11.700
Perfluorocarbons (PFCs)	6.500–9.200
Nitrogen trifluoride (NF_3)	17 200
Sulphur hexafluoride (SF_6)	23.900

There are two methodological approaches to calculate the carbon footprint: bottom up which is called *Process analysis* and top-down is called *Environmental Input- Output analysis*. Both of these processes have corresponding advantages and disadvantages in constructing a full life assessment (LCA) and capturing the impacts of the life cycle [4]. The first method, bottom up, is based on the process analysis (PA). It can be used to determine the carbon footprint of an individual product and PA provides more information about the environmental impacts. The second method, top-down, is based on environmental input-output analysis; it can be used when there is a need for a larger scale of footprint impacts on environment in an economic way to establish the calculations [4].

The product life cycle from cradle to grave in the process analysis method is divided into several processes, where each one of these processes has inputs and outputs. Moreover, the outputs of one process might be the inputs for a new process. Each process usually requires both materials and energy inputs. Whereas, the output of the process is either the refined material or in some other cases the waste produced by process [13]. In Figure 1, a single process in the process analysis method is modeled.
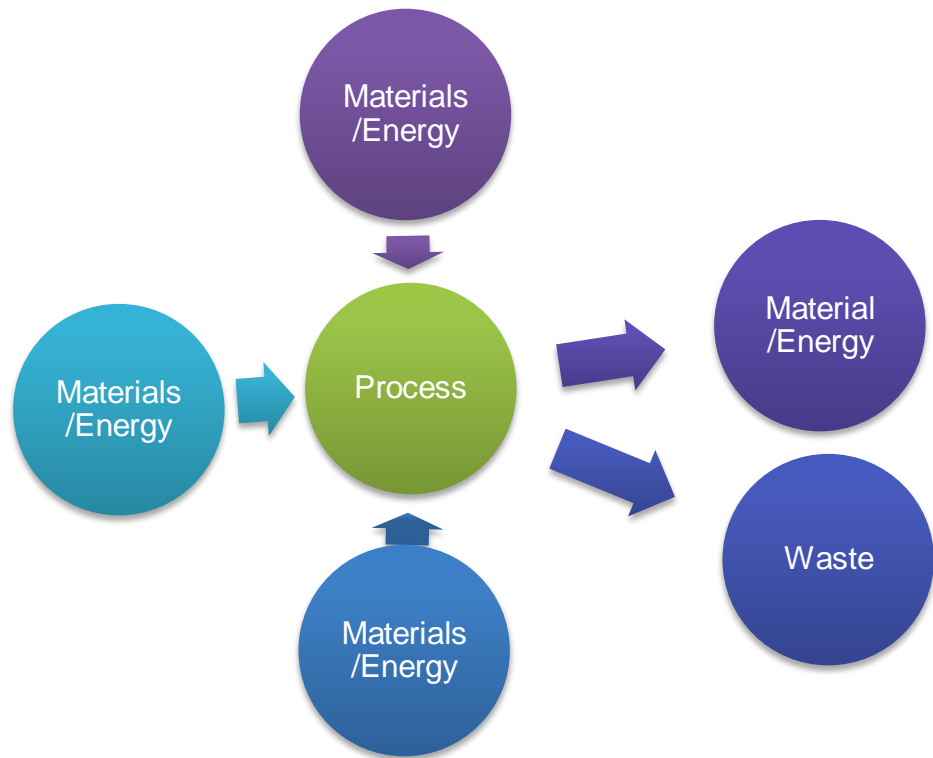
Figure 1. *Single process in process analysis*

The modeling of the product is established by connecting all the processes together using the input and output-flows in the complete life cycle that can be seen in Figure 2. The flows of each process can be specified by mass, volume, energy etc. [13].
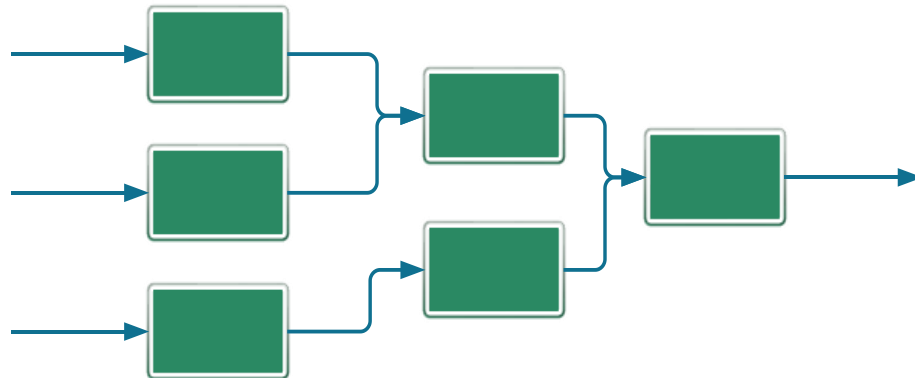
Figure 2. *Several Processes connections and flows [13]*

The input and output analysis life cycle has a detailed and broader view. All the economic activities at a certain level can be provided through the tables of input-output which are economic accounts. The carbon footprint can be estimated in an inclusive and robust way when the tables combined with the reliable environmental account data. The entire economic system is set as boundary in consideration to all higher impacts. The most important advantage of input-output analysis method, is significantly less demands of time and manpower once the model is established in place [4][13]. This can be notice in Figure 3.
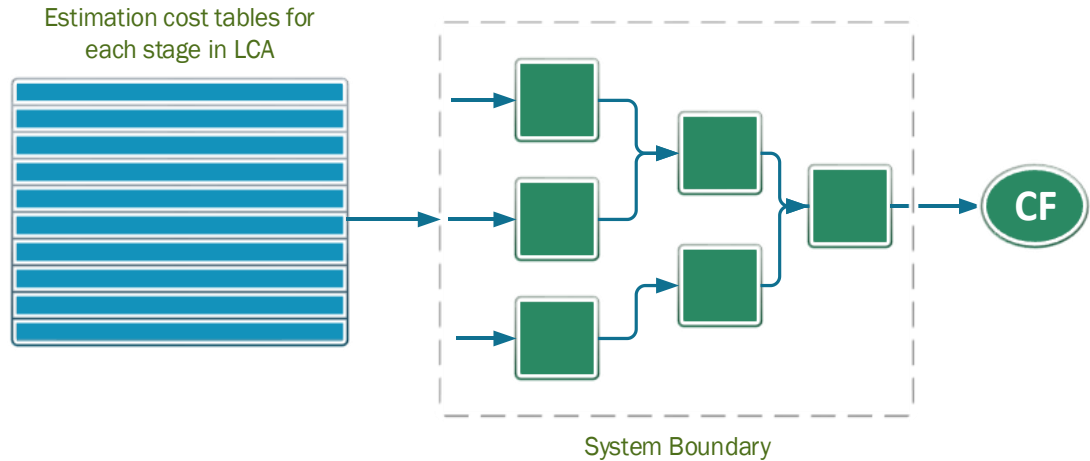
Figure 3. Example of Economic input – output analysis process [13].

However, combining both methods PA and input-output by using hybrid approach will result in depth, inclusive and strong analysis. Hybrid approach will permit in lower-order stages, to maintain the precision and detail of bottom-up approaches. Whereas, the input-output part of the model can cover the higher order stages [14][15][16].

The current state-of art in ecological economic modeling is a *Hybrid-EIO-LCA* method, embedding process systems inside input-output tables [16][17][18].

By calculating the carbon footprint of products through their complete life cycle will allow the companies to collect the required information in order to [7]:

- Recognize opportunities in saving cost.
- Integrate emissions impact within decision making by changing materials, suppliers, manufacturing processes and product design.
- Decrease greenhouse gas emissions.
- Inform the user about the products carbon footprints.
- Distinguish and fulfill the demands from "green" customers.
- Emphasize the corporate responsibility towards environmental leadership.

2.1 Standards

2.1.1 PAS 2050

PAS 2050 is a publicly available specification for assessing product life cycle GHG emissions, prepared by BSI British Standards and co-sponsored by the Carbon Trust and the Department for Environment, Food and Rural Affairs (Defra) [7]. PAS 2050 was developed over 16 month due to several complex issues and a technical matter in the standard by BSI. Therefore, the PAS 2050 standard was published in October 2008 and more than 75 important companies and firms through different sectors and sizes have tested the standard including goods and services [20].

Moreover, the publicity available specification has a guide from the BSI called "Guide to PAS 2050: how to assess the carbon footprint of goods and services." This guide aims to help all the companies, from different sizes and industries, to measure the carbon footprint of their products through the entire life cycle. Furthermore, it is used to identify the possible ways to reduce the amount of emissions and share best practices, tools and frameworks [7].

PAS 2050 is constructed based on actual life cycle assessment methods that are formed through BS EN ISO 14040 and BSEN ISO 14044. In addition, it is supplied with precise requirements for the assessment of the GHG emissions throughout the life cycle of goods and services [19].

ISO 14040 "Environmental management-Life cycle assessment–Principles and framework" describes the details about the LCA process [21]. ISO 14044 "Environmental management–Life cycle assessment–Requirements and guidelines "is on life cycle inventory studies and life cycle assessment studies [22]. Therefore, the PAS 2050 standard is established based on LCA [20].

By multiplying the mass of a particular greenhouse gases (GHG) by its global warming potential (GWP), the Carbon dioxide equivalent (CO_2e) is calculated. For instance, the GWP of CO_2 is equal to 1 whereas, the other types of Greenhouse gases are converted to their carbon dioxide equivalent. The value of this equivalent is measured on the basis of their per unit radiative forcing. In addition, the CO_2e calculation is applied by using 100-year global warming potentials specified by the Intergovernmental Panel on Climate Change (IPCC). The final value of CO_2e is in kilograms. There are various values of the GWP starting from the range of 1 over 20000. For example the global warming potential value of methane is 25 and the value of nitrous oxide is 298. There is a list in PAS 2050 of the GWP values of greenhouse gases which can be used in the calculations. For example, hydro fluorocarbons, per fluorinated compounds, fluorinated ethers, perfluoropolyethers, hydrocarbons and other compounds are controlled by the Montreal protocol and are available in the list [19][20].

The calculation of the carbon footprint in PAS 2050 comprises five basic steps: building a process map (flow chart), assess boundaries and materiality, collecting data, calculating the footprint, checking uncertainty that can be seen in Figure 4.
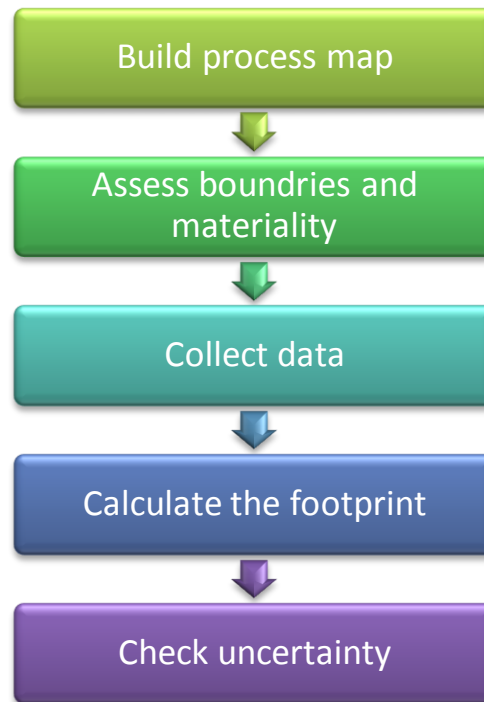
Figure 4. PAS 2050 five steps to calculate carbon footprint [7].

The first stage in PAS 2050 is to *build a process map* which is an essential step to describe all types of materials, processes and activities that are included in the life cycle of the product. It is necessary to understand the flows in the product's life cycle, because the flows are ranging between a complex system and an easy one. There are two types of systems used in this step, business-to-consumer and business-to-business. In the business-to-consumer system, the carbon footprint calculations map process will have the structure as shown in the Figure 1. The stages begin with the raw materials, manufacturing processes, distribution, consumer use and finally the disposal/recycling [7].

Figure 5. Carbon footprint stages of the life cycle product based on Business–to–consumer [7].

However, the business–to–business map stages of a product can take a different shape that ends at the step of distribution of product to another manufacturer. This type is in agreement with the cradle–to–gate approach in BS EN ISO 14040, which means the product life cycle starts from raw materials to the gates on the second manufacturer. These stages are mentioned in

Figure 6 below.

Figure 6. *Carbon footprint stages of the life cycle product based on business–to–business [7].*

The second stage in PAS 2050 is *checking the boundaries*. This step outlines the product life cycle stages as well as the inputs and outputs that should be added in the assessment. If the Product Category Rule (PCR) is available for the product, then the system boundaries should be used as it is outlined in the ISO 14025 standard type III labels [7].

Otherwise, the system boundary should be clearly defined if there is no PCR for the product. Due to the wide range and differences in the products and their environmental performance, the EPD® (Environmental Product Declaration) created a set of rules based on the product category. These rules are called Product Category Rules (PCR) that are founded to enable transparency and comparability to the overall requirements [23].

When setting the system boundaries for a product life cycle, it is necessary to involve in the process all the direct and indirect emissions which are produced by the product as well as used and disposed/recycled. Furthermore, the insignificant materials emissions can be eliminated if the results are less than 1 % of the total emissions. Besides, there are some other emissions can be excluded such as human inputs to processes, consumers transport and also the transportation that is done by animals [7].

The third stage is to *collect data*, this data is supposed to be accurate and more readily comparable carbon footprints. Moreover, the data must be in consistent with the Data Quality Rules that is stated in PAS 2050. The Data Quality Rules are the following [7]:

- Technology coverage (for instance, if the data is connect to an exact technology or a combination of several technologies)
- Time-related coverage (e.g. age and the lowest length of time of data which are collected)
- Geographical specificity (for example, district, country, region data)
- Accuracy of the information (such as models, data and assumptions)
- Precision

Also, the following points shall be considered [19]:

- Completeness
- Reproducibility

- Consistency
- Data sources with reference to the primary or secondary nature of the data

Furthermore, there are two kinds of data: *activity data* and *emission factors*. There two types of data are important to calculate an activity of a carbon footprint. Activity data indicates the amount of material and energy required to manufacture the product–see Figure 7. Whereas, emission factors refers to converting the amounts obtained into GHGs emissions. For instance, the quantity of GHGs produced per 'unit' of activity data (e.g. Kg GHGs /kg input). Both activity data and emissions factors can be obtained from either primary or secondary sources. Primary data states the direct measurements that have been made to refer to an exact product's life cycle. However, secondary data indicates about external and more overall measurements of comparable processes or materials such as industry reports [7].

Input/output	Energy used	Direct gas emissions	Distribution/ transport
•Amount and type of entire inputs and outputs •Each process should has the following steps: •Material inputs •Product output •Waste •Co-products	•Source, type and amount of all energy used: •Electricity •Other types of fuel	•Amount and type of direct GHG emissions	•Vehicle type and average distance •% full on return journey •% shared or full with other types of products

Figure 7. Common activity data per unit of finished product [7].

Calculating the footprint is step number four. In this stage the carbon footprint is calculated based on the given equation in Figure 8. The calculation of carbon footprint is done through multiplying all the activity data of product life cycle by their emission factors. Calculating the mass balance is essential in order to make sure that all the input, output and waste are accounted for. After calculating the GHG emissions for each process, these values are converted into CO_2 by using the GWP factors listed in PAS 2050. The real calculation contains multiple steps which include doing the calculations for each stage of a product. Finally the net quantity of GHG emissions represents the final amount of carbon footprint [7].

Sometimes there are some specific cases where the GHG emission sources have distinctive features that might have an effect on the assessment and require more guidance through PAS 2050. These special treatments are delayed emissions carbon storage and allocation with guidance [7].
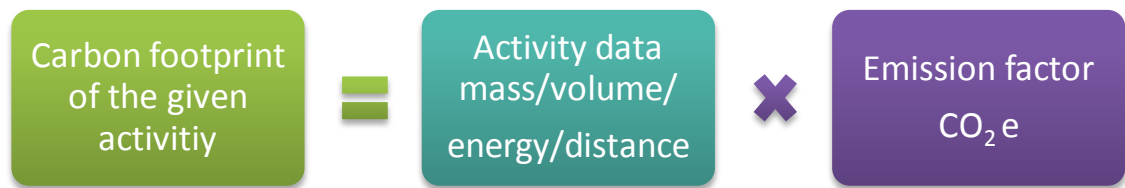
Figure 8. Equation of Footprint calculations [7].

The final step in the PAS 2050 guide is *checking the uncertainty*, even though it is optional. The aim of this stage is to evaluate the result of footprint in order to avoid or minimize uncertainty. The uncertainty of carbon footprint is derived from two sources: technical uncertainty and natural variability. The reasons behind technical uncertainty are limited data quality, wrong assumptions, incomplete modeling, ineffective sampling and more flaws in the footprint calculation. Natural variability does not need to be quantified because the carbon footprint is accounted as an average or representative figure [7].

There are several reasons for the technical uncertainty including:

- wrong assumptions
- limited data quality
- incomplete modeling
- ineffective sampling
- flaws in the calculation itself

Uncertainty calculations are done based on Monte Carlo analysis approach, the calculations consist of three steps. The first step is to define the probability for each input that is determined by:

- the distribution type
- upper/lower bounds of the input value to reach 95% confidence
- correlation factors

Then the input amounts are repeated randomly according to its distribution and later the new values of the CF is recorded. Finally, this procedure is repeat for all input values, thus probability density of the CF is formed. The repetition of uncertainty value can be stated as a '±%' or a range of values [7].

2.1.2 ISO/TS 14067 Standard

The standard was suggested in the first meeting of the ISO/TC (Technical Committee) 207/WG (Working Group) 2 in April 2008. After that, the standard has gone through a lot of developed processes by several countries such as China and Argentina, and

experts which acknowledged a lot of feedbacks and comments from the international involvement [24].

Due to high concerns of the customers and shareholders regarding the environmental impacts of the goods products and services in the market, the ISO 14067 was published and released in May 2013 as a Technical Specification. The standard will still be reviewed again to determine whether it will be published as an international standard or revise it [10].

ISO/TS 14067 identifies principles, requirements and guidelines for the quantification and communication of the carbon footprint of products (CFP). It contains both goods and services, based on GHG emissions and removals over the life cycle of a product. These previous standards are based on environmental labelling and environmental management including [10]:

- ISO 14020:2000, Environmental labels and declarations-General principles.
- ISO 14024:1999, Environmental labels and declarations-Type I environmental labelling–Principles and procedures.
- ISO 14025:2006, Environmental labels and declarations-Type III environmental declarations–Principles and procedures.
- ISO 14040:2006, Environmental management-Life cycle assessment–Principles and framework.
- ISO 14044:2006, Environmental management-Life cycle assessment–Requirements and guideline.

There are two main goals in the use of this standard. The first objective in the life cycle aims to *standardize the quantification principles and procedures of the Carbon footprint of products*. A Complete CFP Case study based on ISO 14067 should include a quantification process of CFP. As well as a report based on the results from quantification and a critical review established on ISO 14044 [10]. The critical review process in the ISO 14067 should ensure that: the approaches used to implement the LCA are dependable on the ISO, scientifically and technically valid, the data used are correct and acceptable and linked to the goal of the study, the interpretations reflect the restrictions of the goal in the study and the study report is apparent and reliable [22].

The critical review is required in the CFP quantification stage, although there is a confirmation from a third party that verifies particular requirements in the study. Furthermore, if the CFP study is planned to be publicly available, the CFP communication should be fulfilled and provided through the CFP study. There is no purpose of including a third part verification when there is a disclosure report of CFP [10].

The second objective of ISO 14067 is *to standardize the processes and reports in the communication stage*. If the CFP study is prepared as a publicly available, the process and reports should be provided. There are different forms of communication including a

CFP performance tracking report, a CFP label, a CFP external communication report and a CFP declaration. In the ISO 14067, a standardized format of communication form can be found [10].

The *principles* of ISO 14067 share a parallel set of principles of both PAS 2050 and WRI/WBCSD while assessing GHG emissions. These sets of principles are relevance, completeness, consistency, accuracy and transparency. However, the ISO 14067 has anticipated a new set of principles to be added, containing [10]:

- Coherence: it is about selecting perceived evaluation rules to guarantee equivalence between diverse materials inside of the same classification.
- Avoidance of double-counting: this principle is used in order to avoid double counting of GHG emissions and removals. It is used in situations where the electricity emission factors are used by the supplier.
- Participation: the goal of this rule is to allow all types of the interested parties to be involved in the developing and carrying out the carbon footprint product communication programs.
- Fairness: this principle is meant to highlight that the ISO 14067 is used to study a CFP assessment and communication based on a one impact classification called the climate change. The reductions in GHG emissions should be separated from the carbon footprint emissions.

The most distinctive feature about ISO 14067 is that it focuses on results of the communication with a third party to clarify the difference with PAS 2050. Therefore, these new principles will allow the possibility to compare the results of GHG as well as the transparency in communication.

There are four *System boundaries* that are used in ISO 14067, in order to define and cover all the stages of product life cycle in the LCA studies as well as including the GHG emissions within the stages. The four options of system boundaries are [10]:

- Cradle-to-grave: a cradle-to-grave system boundary comprises the calculations of the emissions and wastes of a full life cycle of the product, starting from the raw materials, manufacturing, distribution, consumer use and disposal/recycling. [19]. This option is recommended to use in ISO 14067 due to the chance to stimulate the end of life phases.
- Cradle-to-gate: a cradle-to-gate system boundary includes the calculations of emissions and removals starting from the raw materials until the point at which the product leaves the manufacturer to other producers and suppliers [19].
- Gate-to-gate: this system boundary option quantification contains the emissions and removals arising from diverse organizations in the supply chain. This approach is implemented when there are several obstacles in collecting data of emissions starting from the cradle until the gate stage.
- Partial CFP: a partial CFP consists of the emissions and wastes from a limited number of remote phases.

The last two approaches in system boundaries, gate-to-gate and partial CFP indicate various difficulties. Especially when it is required to obtain the data of raw materials

and manufacturing that are not available in LCA databases. Additionally, the availability of the sensitivity analysis in ISO 14067 will allow refining the system boundaries. The sensitivity analysis should be used to validate and support the decisions, when the life cycle stages of CFP are eliminated from the study. Then the sensitivity analysis is documented in the CFP report. Without providing the suitable sensitivity analysis report, the manufacturers will not have the opportunity to remove any of the life cycles [10].

In ISO 14067, the *function unit* can be either a product or a service. The functional unit of the product system should be clearly specified and in consistence with the scope and goal of the CFP study. The main objective of a functional unit is to give a reference to the inputs and outputs that are linked. Hence, the functional unit has to be precisely measured and defined. On a self-selected product unit basis, a CFP results can be reported. The CFP results might be stated in conditions of service provided. The results of CFP study will be documented in the report as a mass of CO_2e per functional unit [10].

The *unit of measurement* in ISO 14067 standards is carbon dioxide equivalent (CO_2e) which is similar to other types of GHG standards. The Other GHG emissions, such as CH_4, SF_6, Hydrofluorcarbons (HFCs) have to be involved in the calculation process due to a higher global warming potential impact than CO_2 emissions [19]. However, CO_2 is the most used unit of measurement in numbers of CFP studies and carbon labelling programs [10].

The emissions produced in the *Use phase and end-of-life phase* of a product according to ISO 14067 are still under evaluation, whether these emissions should be excluded or included in the studies [25]. The reason behind these doubts is the various ways of using the product by users such as maintenance and replacements. Thus, the usage phase might be excluded in several CFP studies. However, the impact of the use phase and end life phase has a high effect on the CFP calculations. In order to support and establish a complete CFP report the use and end-of-life phases should be included in the study [10].

To solve this issue, ISO 14067 has offered a guidance to regulate the use stage and use profile. The guidance defines the assumptions and underlying the assessment of emissions generated in the use phase. In a three step process can summarize this guidance [10]:

- Step 1: aims to verify the service life information, describes the use conditions and functions of the product. In addition, identifies the certain usage pattern of the product in the market.
- Step 2: when it is not possible to justify the usage phase, the definition of the use stage can be established based on published technical information. The technical information can be used such as national guidelines, international standards,

industry guidelines and documented usage patterns in the market selected. Applicable if the first step cannot be accomplished.

- Step 3: in this step, the use profile is determined based on the manufactures or organizations recommendations that are implementing the CFP studies and their endorsements for a proper use. It can be used when the second step is not possible to archive.

The last part before the communication stage is the preparation of CFP report that should document all the results of calculations of the study. The ISO 14067 offers a standard format of a basic assessment process such as functional unit, system boundary, applicable assumptions and result of the life cycle study. This type of report will allow in a clear way to follow up in the communication program. The other information that is required in report [10]:

1. Specific GHG emissions and removals that are connected to the life cycle where they happen, in addition to absolute and relative contribution of each life cycle stage: the generation of electricity, from fossil carbon sources, from biogenic carbon sources, aircraft transportation and direct land use change (dLUC).
2. A sensitivity analysis of the GHG emissions and removals.
3. Ratio indicators can be provided and calculated in the communication program.
4. Applicable assumptions and descriptions of the use phase and end-of-life scenarios and indications of agreements regarding comparisons (optional).

The aim of ISO 14067 life cycles is to offer directions and requirements for companies and organizations which determine to communicate the CFP results. The way of CFP communication can occupy the form of a CFP performance tracking report, a CFP declaration, a CFP external communication report or a CFP label. Therefore, the main goal of the CFP communication is to allow the consumers to be involved in the decisions, which can have a high effect on the GHG emissions. The information is given by the user of a product especially during the usage profile in order to make choices on end phase and recycling. Moreover, the CFP Communication can be revealed to public after either being verified by a third part or being supported by a CFP disclosure report. In the ISO 14067, there is a fixed template of CFP disclosure report, which includes the product information, previous CFP case report that shows the critical review, contact information, CFP- PCR (Product Category Rule) if available , type of CFP (partial or full), etc. [10].

As mentioned before about the CFP communication forms, CFP label is one of these forms. Nowadays, the CFP label refers to as carbon label which points to direct customer communication. The CFP label states to only one impact category that does not represent the type I of environmental label. The ISO 14067 published regulations when the CFP label is used in a report that intended to be as a publicity available including:

- CFP label is given to the products that fulfill the CFP communication program requirements.

- Recognize the specific criteria that are corresponding to the CFP results values of the study. The set of criteria are established based on using CFP- Product Category Rule.
- The CFP communication operator has to set the levels and select the criteria based on the CFP-PCR rules which are matching with ISO 14067 requirements and clarify the label validity date. In addition, the possibility of the user to determine other non-CFP criteria.
- The CFP communication program can involve several parts such as private organizations, public firms, international or regional.

Another method of CFP communication can take both forms of CFP external communication report and CFP performance tracking report. The objective of these two forms is to establish the CFP communications between business to business, as an alternative to direct communication with consumer. In other words, the CFP performance tracking report allows comparing the values of the study for each product within the same organization. Whereas, the CFP external communication report allows for external communication in order to compare the CFP results with other companies. Table 3 illustrates the comparison of the two reports.

Table 3. Comparison of the CFP communication tracking report and CFP External communication report [10][26] .

	CFP performance tracking report	CFP External communication report
Third party disclosure report or verification	Mandatory	Mandatory
Level	Business-to-Business	Business-to-Business
CFP–PCR	Optional	Optional
Inclusions	System boundary	System boundary
	LCA results	LCA results
	Company information	Company information
	Graphical representation of LCA process, contributions of the changes, product information, LCA Interpretation	Product information, LCA Interpretation

2.1.3 The GHG Protocol: A Corporate Accounting and Reporting Standard

The World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD) published the Greenhouse Gas Protocol in 1998. The GHG Protocol is an accounting tool used generally by organizations, governments and businesses in order to comprehend calculate and regulate GHG emissions. Moreover, the Protocol mission is to help the developing countries by offering a GHG accounting tool and reporting standards, which are internationally recognized. As well as the

promotion of the GHG Protocol use around the world to reach low emissions worldwide [28].

The GHG Protocol Initiative encompasses two standards that are independent from each other but somehow related [28]:

- GHG Protocol Corporate Accounting and Reporting Standard (2004): this standard contains guidance on how to calculate and report about the GHG emissions for the organizations.
- GHG Protocol Project Quantification Standard (2005): this standard is about a guidance of the reduction calculations based on GHG mitigation tasks.

Later, the GHG protocol published new two standards [27]:

- GHG Protocol Corporate Value Chain (Scope 3) Accounting and Reporting Standard (2011): the main objective of this standard is to provide standardized procedure that would help the organizations to calculate and report their value chain GHG emissions. In addition, to provide solutions for the companies to make an effort for reductions. It is used with complement to the GHG Protocol Corporate Accounting and Reporting Standard.
- GHG Protocol Product Accounting and Reporting Standard (2011): a standardized approach to calculate and publicly report the GHG emissions and waste for a certain product's life cycle.

The GHG Protocol Corporate Accounting and Reporting Standard and guidance have been established based on the following purposes [28]:

- In order to support corporations in organizing a GHG inventory which characterizes an accurate and reasonable values of their emissions, by using of standardized methods and principles.
- A way to clarify and minimize the rates of gathering a GHG inventory.
- To offer information which can be used in business to form an effective approach to control and decrease GHG emissions.
- In order to raise coherence and transparency in GHG accounting and reporting between several enterprises and GHG programs.

The *principles* in GHG accounting and reporting are [28]:
- Relevance: The GHG emissions of the company are reflected precisely in the GHG inventory in order to assess the user's needs in the company to make decisions.
- Completeness: All the GHG emissions origins and activities are measured and reported within the selected inventory boundary. In addition, the report should reveal and explain if there is any particular elimination.
- Consistency: allows the comparing of different emissions over time based on the use of reliable methods. Moreover, any changes in inventory boundaries data, factors or methods will be shown clearly in the document.
- Transparency: Report all applicable matters in a clear way that is based on an audit trail. Accounting and measurements practices as well as data sources used are clarified and revealed of any relevant assumptions and references.

- Accuracy: to make sure that the calculations of GHG emissions are steadily and close to the actual emission values and those values can be evaluated. Further, the uncertain measurements are decreased as much as possible. To assist users towards accomplishing adequate accuracy to make proper decisions.

There are two methods that companies can apply to consolidate GHG emissions while setting an *organizational boundaries* based on the corporate accounting and reporting standard: *the equity share* and the *control methodologies*. The equity share method: a company quantifies their GHG emissions from processes based on its share of equity in a single process. The equity share reflects economic interest, which is the range of limits that a company has to the risks and rewards as a result of an operation. Normally, the corporation percentage ownership should be coordinated with the share of economic risks and rewards in an operation. Consequently, the equity share will usually be the same as the ownership percentage. The second method in setting organizational boundaries is the control approach. An organization only accounts for total percent of the GHG emissions generated from processes, when it has control over the operation. Whereas, the processes without control in the company should not be accounted for their GHG emissions. There are two approaches to define control, in financial or operational terms [28].

Setting operational boundaries such as *direct* and *indirect* emissions will help organizations to manage the GHG emissions threats and reduction in efficient and innovative ways that are existed in the value chain. The GHG emissions generated from sources which are controlled by the company are called direct GHG emissions. Whereas, the emissions that are a result of the activities of the organization but happen at sources controlled by another organization are called indirect GHG emissions. Three scopes (scope 1, scope 2 and scope 3) are specified for GHG accounting and reporting objectives, in order to enhance transparency, help define indirect and direct GHG emission sources, offer service for various forms of companies, climate policies and business goals. In this standard, both scopes 1 and 2 are precisely described to guarantee that two or more organizations will not address for emissions in the identical scope. Hence, the double counting in the scopes will be considered before using the GHG programs. The scopes in the GHG Protocol can be classified as follow [27][28]:

- *Direct GHG emissions (Scope 1):* GHG emissions that are produced from combustion such as vehicles, furnaces, boilers and emissions generated through chemical production. Thus, the direct GHG emissions arise from sources are controlled or maintained by the same organization. However, GHG emissions not covered by the Kyoto Protocol such as NOx (mono-nitrogen oxides) and direct CO_2 emissions from the combustion of biomass and shall not be involved in scope 1 but reported individually.
- *Electricity indirect GHG emissions (Scope 2):* This scope is related to the GHG emissions that are produced from purchased electricity that is used by the organization. The purchased electricity means the electricity that is brought to the organizational boundary of the organization.

- *Other indirect GHG emissions (Scope 3):* Scope 3 focuses on other types of indirect GHG emissions which are related to the activities of the organization. These types of GHG emissions are generated from sources that are not controlled or maintained by the organization and it is an optional reporting classification. Extraction and manufacture of obtained materials, transportation of the product and the consumption of fuels use of products and services are examples of activities in scope 3. Figure 9 shows the three different scopes of GHG protocol.
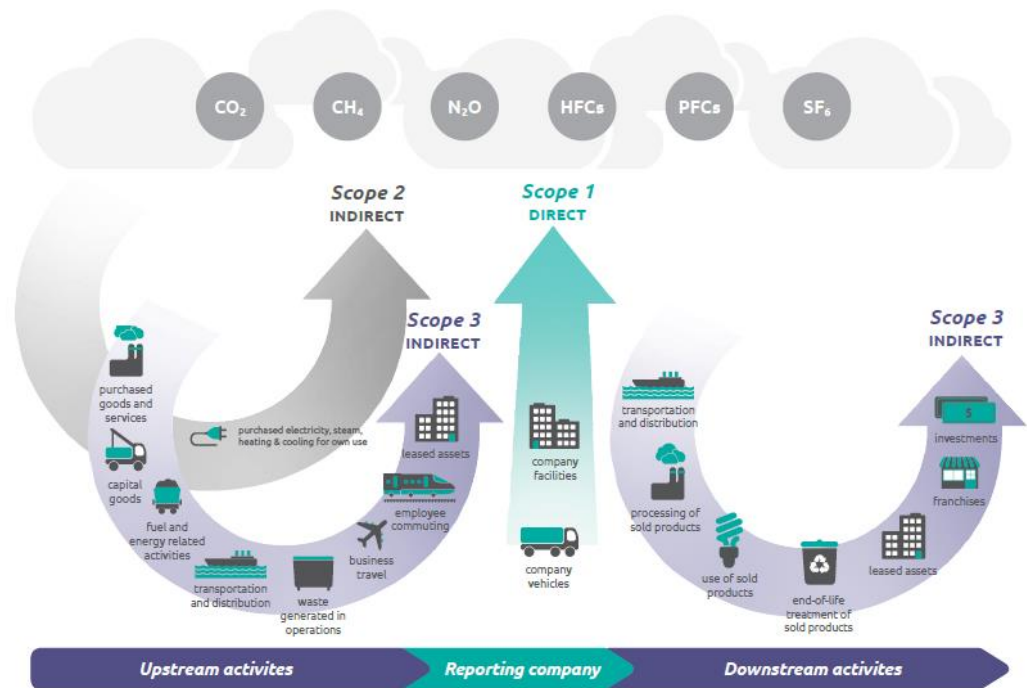
Figure 9. *Overview of GHG Protocol scopes and emissions across the value chain [27].*

Organizations according to this standard are required to *track emissions over time* in order to fulfill diversity of business objectives, containing [28]:

- Dealing with risks and opportunities
- Creating GHG goals
- Addressing the requirements of investors and other shareholders
- Public reporting

It is recommended for the organizations over time to define a regular performance datum in order to compare their current emissions with the previous calculations values of GHG emissions. The base year emissions represent the first step during the performance datum which main function is to track the emissions. The second step, to achieve a reliable tracking of emissions over time, is to recalculate the base year emissions while the corporations experience important structural changes, for instance divestments, consolidation and acquisitions [28].

After setting the inventory boundary, the organizations can establish their GHG emission calculations by following the stages mentioned in Figure 10 below.
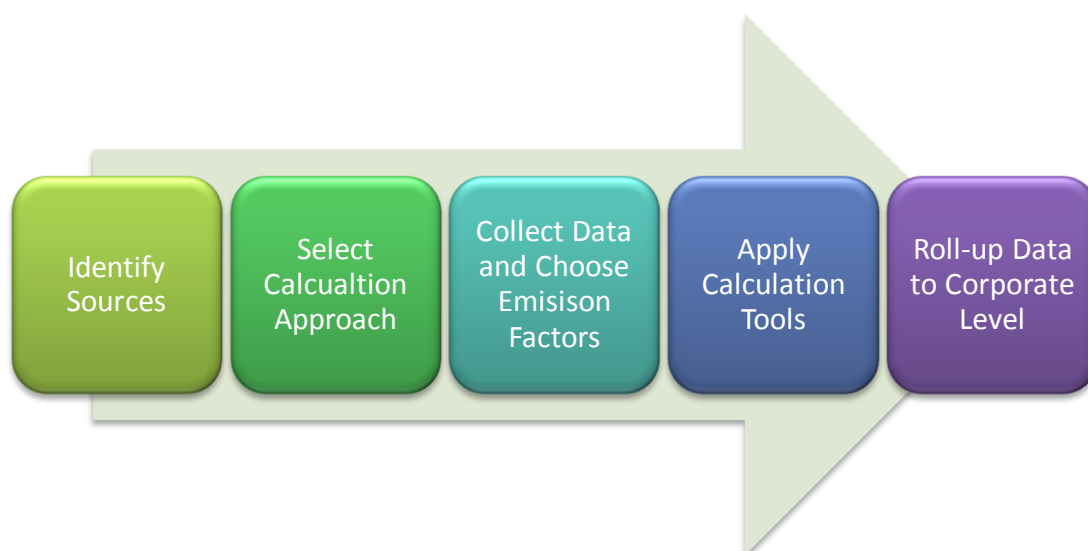
Figure 10. *Stages in classifying and calculating GHG emissions [28]*

The last stage in the standard is the reporting of GHG emissions. The reported information should be accurate, consistent, transparent and complete. It is also required to report at least scope 1 or scope 2 in the GHG Protocol Corporate Standard.

Consequently, a GHG emissions report is meant to be public and according to the standard, the report has to contain the following points [28]:

1. Information about the organization and inventory boundary: It should include, organizational boundary, operational boundary, whether Scope 3 is involved, types of activities that are included and reporting period.
2. Information about emissions:

- All GHG trades e.g. sales, purchases, transfers or banking of allowances have to be dependent from the total scope 1 and 2 emissions.
- Each scope has separate emissions data sheets.
- All six GHGs (CO_2, CH_4, N_2O, HFCs, PFCs, SF_6) emissions data are defined individually in tons of CO_2 equivalent and in metric tons.
- Results of base case year and clarifications of recalculations values.
- Illustration of the most important modifications that changes the values in the base year emissions recalculation such as adjustments in reporting boundaries or calculation approaches, etc.
- Direct CO_2 emissions produced biologically sequestered carbon, for instance CO_2 from burning biomass should be reported separately as emission data.
- Provide a list of the calculation tools that have been used to quantify the GHG emissions, in addition to the calculation methods such as links or references.
- Detailed eliminations of services, sources and/or processes.

3. Optional Items to be encompassed:

- Provide scope 3 emissions data and operations if relevant.

- Provide subdivided emissions data for instance by source types (stationary combustion) or by activity type (electricity production) or by country and facilities.
- All types of emissions related to producing of electricity, steam or heat that is sold externally for other projects.
- Detailed information about the performance which is made in contrast to the external and internal benchmarks.
- Other types of emissions (e.g. CFCs-Chlorofluorocarbons) are not included in Kyoto Protocol should be reported independently from the scopes.
- Information regarding the suggested procedures for GHG emissions management and reduction platforms.
- Reporting on ratio indicators.

Table 4 illustrates a comparison between the three previous standards mentioned before.

Table 4. *A comparison of PAS 2050, ISO/TS 14067, The GHG Protocol [7][10][28].*

§	PAS 2050	ISO/TS 1§4067	WRI/WBCSD: The GHG Protocol
System boundaries	Cradle-to-grave Cradle-to-gate	Cradle-to-grave Cradle-to-gate Gate-to-gate Partial CFP	Cradle-to-grave Cradle-to-gate§
Refining system boundaries	Not available	Sensitivity analysis	Not available
Functional unit	Product Service	Product Service	Product Service
Use and end–of–life phases	Can be omitted if cradle-to-gate is chosen as system boundary	Must be included if these two phases can be adequately simulated and the results are intended to be publicly available	Can be omitted if cradle-to-gate is chosen as system boundary
CFP study report	No	Yes	Yes
Quality assurance	Third party verification Self- Verification	Third party verification CFP disclosure report	Third party assurance Self–assurance

2.2   Carbon footprint Labels

Eco–labelling provides proper information about the environmental aspects of products and services to customers through the label. It also helps a customer to contribute in sustainable development objectives by making the right choice [29].

Environmental labels offer customers a chance to be informed about the aspects of product that are not being clear to them. Moreover, the environmental labels provide an opportunity for customers to compare different products in the market. By providing this information, the customer will select and acquire the environmental products that will reduce the environmental impacts of their regular activities. In addition, labels will provide some instructions for customers on how to use appropriately and securely recycle/dispose products and packaging [30].

The first label program was released in 1947 by the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA). It involves the registration and producers of pesticide with the U.S. Environmental Protection Agency [30].

Due to increasing demands from costumers in the US during the 1980s to acquire green products, the numbers of the environmental products have raised in the markets [31]. Afterwards, some products were introduced to the US market in a great numbers during the 1990. These products were having claims such as biodegradable, recyclable and eco-friendly [32]. Therefore, the Federal trade Commission (FTC) published guidelines to control the large numbers of environmental claims and to help in green marketing [33]. According to ISO standards, the environmental labels are divided into three different types of labels.

The labelling programs are categorized into two types of environmental labels verification, first-party and third-party verification. The first party verification is a basis associated in marketing products and services, for instance "company supports WWF" (World Wide Fund for Nature). As well as advertising for the positive features of the products. Whereas, the third party verification is executed with separate and different foundation that grant the products a certain type of labels according to specific standards and environmental criteria. This verification can also be categorized into mandatory and voluntary in the environmental labelling programs. Voluntary label programs are normally the positive and neutral characteristics of the product. While, the mandatory label programs usually provide warnings or inform about hazards [30].

Therefore, the environmental labels can provide a comprehensive range of information. It aims to guide and educate as well as to promote of the environmental awareness among the customers. The mandatory label programs can contain data about the components and ingredients of the product in addition to the substances that are excluded from it. Furthermore, it is possible to get the required information from these

labels on the right use and storage of the products. The voluntary labels can offer certain information regarding the environmental attributes such recycled contents. Additionally, these labels can inform about the entire life cycle of the product starting from production, use of the product and disposal and even give facts about the energy consumption during manufacturing. The most important objective of the environmental labels programs is to contribute about explicit environmental attributes such as a complete Life Cycle Assessment (LCA) or carbon footprint of a product [30].

The numbers of the carbon footprint labels are still few. Some labels indicate the value of carbon footprint and other labels compare two products with each others to clarify the lowest amount of CF among the product group. The value of the carbon footprint can be usually expressed in grams per function unit.

2.2.1 The Carbon Trust

The Carbon Trust is an association established by the support of the UK government in 2001. The association's main goal is to calculate, decrease and communicate CF emissions through the supply chain in order to accelerate the transition into a low carbon economy. Furthermore, the carbon trust incorporation with British Standards Institution BSI has developed a specifications guide called PAS 2050 that provides methods and specification to measure GHG emissions [20]. The Carbon Reduction Label is their carbon footprint label. Figure 11 represents the label of the company.

Figure 11. Carbon Trust Label [20].

The Carbon Reduction Label on a product illustrates that the company is aware of the GHG emissions and devoted to reduce the CF emissions. Additionally, the label provides the total CF value in CO_2e, which is calculated from the complete life cycle of the product, including raw materials, manufacturing, distribution, use of the product and disposal. Moreover, the Carbon Reduction Label allows comparing the CF of a product to other related products. There are several products that already have this label and following the instructions and objective of the Carbon Reduction Label such as, Walkers for goods, Tesco for light bulbs and Halifax web Saver account [34].

The Carbon Trust association provides a complete carbon footprinting guide in order to provide instructions on how to estimate the carbon footprint for organization, product and value chain. A typical footprinting process consists of four stages. The first stage is the measurements including: building a process map, defining the boundaries, collecting both primary data and secondary data, assessing materiality, measuring the carbon footprint and validating it. Subsequently, the values obtained are evaluated by a third party to verify that the results. The results then are checked if they correspond with secondary data and comparability rules of the Carbon Trust Label, PAS 2050 and the Code of Good Practice. Afterwards, the emissions values are inspected to clarify the critical highest levels of CF, in order to propose a new opportunity to decrease the CF. The last stage is the communication part that is the most significant part in the process to identify the CF and precede with the reduction plans [9].

2.2.2   Climatop

Climatop is created by two associations: Ökozentrum Langenbruck and myclimate in 2008. Climatop is a non-profit Swiss organization located in Zurich. The Climatop carbon footprint label is "approved by Climatop" that can be seen in Figure 12. The label is still under progress and will be introduced to the market in the near future [35].

The aim of this label is to assist customers to select the products which are environmentally friendly from a group of other products. In addition, the manufactures will show the commitment in climate changes that will enhance the product marketing [37].

In order to obtain a "approved by Climatop" label license, the product should prove that the emissions of CO_2 is 20% lower than other products or services in the same category. Furthermore, the product should accomplish different social standards and environmental requirements [35].

Figure 12. Climatop label [35].

The calculation of the carbon footprint in the Climatop is based on the complete life cycle of the product. Thus, the final measurement values of CO_2 emissions are established by including the values emitted from raw materials, manufacturing, transportation to consumers, use of the product and disposal (e.g. recycling). Most of the data are collected from the Ecoinvent databases. Ecoinvent is a non-profit organization established by ETH university domain and Swiss Federal Offices to create a world databases for the Life Cycle inventories [61]. There are several products which are using the label such as Dyson for Hand dryer and Dirk Rossmann GmbH for Diapers. These products show the CO_2e equivalent [35][36].

2.2.3 Carbon Counted

Carbon Counted is a Canadian non- profit association that applies a unique approach. This approach will allow organizations to estimate online the CF of products or services based on current standards CFs, then download the Carbon counted label through their website (see Figure 13). By using the Carbon Counted solution, the organization will be able to select the most suitable standards which are matching with their requirements. Subsequently, to calculate the CF, to have it verified by a third party then to finally obtain the Carbon counted label [38]

Figure 13. Carbon Counted Label [39].

The amount of CO_2 emissions is shown in figure 14 as a total value of CF in Kg equivalent. The label uses several standards to verify the calculations, for instance ISO: 14064 standards, ISO 14025:2006, PAS 2050 and GHG Protocol [38].

2.2.4 Japan CFP Label

The first draft of this program was called the carbon footprint of Products (CFP). The Japan Environmental Management Association for Industry (JEMAI) developed the label and changes the title of the label to The CFP communication program. The objective of this program is to highlight the effect of the carbon footprint emissions during the life cycle of the products. Additionally, it aims to motivate the organizations to communicate in order to reduce the amount of the CF emissions into the atmosphere [40]. The CFP label is indicated in the Figure 14.
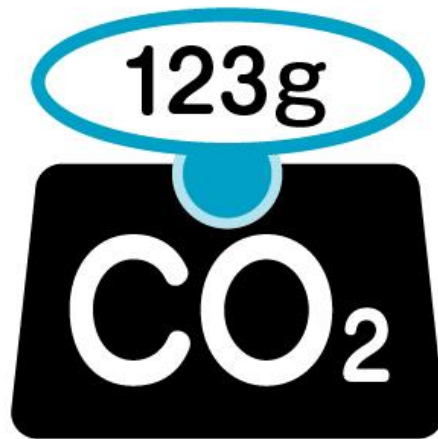
Figure 14. Japan CFP Label [41].

The (CFP) is calculated for the entire life cycle of a product based on ISO14040, ISO 14044 and ISO/TS 14067 standards. The value of the CF is expressed by the CO_2-equivalent of GHG emissions. Therefore, the measurement includes the values of CF starting from raw material to disposal or recycling. Later the CO_2e is displaced on the product per grams of the total emission [43].

There are three steps required to get the verification and permission from the JEMAI CFP program to use the label [42]:

- Choosing from the current CFP-PCR or doing some improvement in the CFP-PCR to obtain a different classification.
- CFP Measurements and verification.
- Request for registration and publication of CFP-PCR.

Several products have already got verified by this label, including Fuji Xerox Co., Ltd. for printers and Canon Inc. for ink cartages and printers.

2.2.5   Other Environmental Labels

There are three categories of environmental labels which classified according to ISO, the International Organization for Standardization, called Type I, II, III. ISO aims to create a network of published and development international standards in order to establish a code that will secure the quality and reliability of the products and services [44].

Label type I

The Type I in environmental labelling program is based on ISO 14024 "Environmental labels and declarations-Type I environmental labelling. Principles and procedures". These labels are voluntary which can be managed by several sectors such as private organizations, public use, international and regional. Type I label recognizes products or services that are environmentally desirable among a specific product classification. In order to obtain this type of labels, the products should fulfill a number of prearranged requirements and it requires a third party certification [45].

This type of environmental labelling specifies the multi-criteria and the approval of life-cycle stamps which are normally called as "eco-labelling". It is a more reliable and credible environmental label due to fact that it is executed by government and private institutions as well as certified by external third party [44].

The Climatop label is a type I label which provides information about the greenhouse emissions whether their values are low or neutralized. Some other recognized eco labels related to the type I in the market are the Nordic Swan and EU- Flower labels. These labels are shown in Figure 15.

Labels such as CarbonCounted and Carbon Trust can be accounted as a type I labels despite the fact that these label obtain a lot of detailed information but the information is not adequate to account them to Type III label.
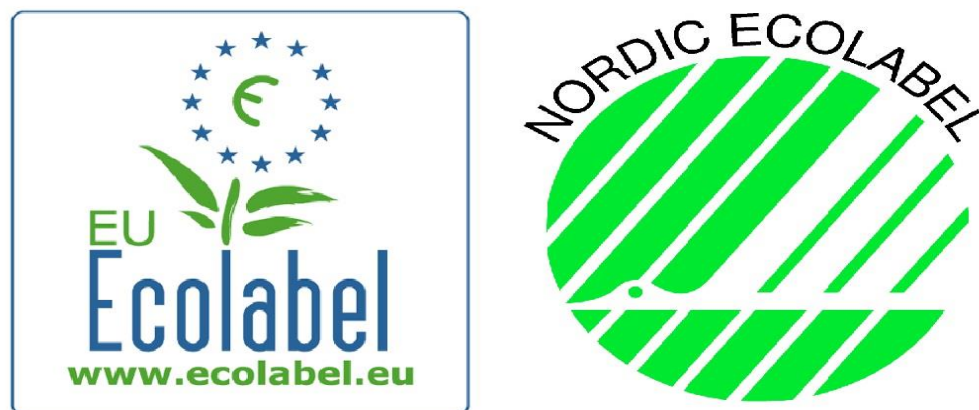
Figure 15. *EU- Flower and Nordic Swan Eco labels [48][50].*

The Nordic swan Ecolabel was established by the Nordic council Ministers and represents the Nordic countries official Ecolabel. The main objective of this Eco label is to encourage the costumers to purchase less environmentally deleterious products by developing guidance for costumers containing environmental criteria for goods and services. One of the most significant goals of this label is to considerably decrease the amount of GHG emissions released [49].

The EU-Flower or the European Ecolabel is an independent association established in 1992. It aims to help the customer to make choices in choosing environmentally friendly products and services. It is classified as Type I label and the criteria purposes to decrease the impacts throughout the complete life-cycle of the product, starting from manufacturing until the disposal [50].

One of the EU projects was "the carbon footprint measurement toolkit for the EU Eco label" and its main purpose is to introduce a reliable and developed tool to calculate the CF in the EU Ecolabel. The final conclusion of the project is to include the CF as a part of the criteria implementation without displaying the CF in the label [51].

Label type II

Type II environmental label is designated in ISO 14021 "Environmental labels and declarations. Self-declared environmental claims (Type II environmental labelling)". As a self-declared label and represent the type II of environmental labels. The aim of this label is to ensure that the self-declared environmental claims are reliable and the absence of any false and inaccurate claims. There are specific requirements for multiple selected claims, such as recyclable. This means that the product is collected and treated in order to reuse it again as a raw materials or complete products. Climatic claims have no precise requirement. However, vague and non-specific claims such as non-polluting and ozone friendly cannot be used [46].

Mobius Loop is one example of the type II environmental labels. It is shown in Figure 16. The symbol or label is utilized to present an environmental claim. Hence, it is generally used for recyclable claims and sometimes for packing purposes. Several forms of the label area available and below in the figure is one of the examples [46].

Figure 16. *Mobius Loop [46].*

Label type III

The type III label is defined in ISO 14025"Environmental labels and declarations. Type III environmental declarations. Principles and procedures". This type of labels provides information about measured environmental impacts of the entire life cycle of a product. Hence, the information about the product will allow the costumers to compare different products from the same category. Based on ISOs 14025 standards, type III labels are mostly meant to be used in business-to-business communication and not in the business-to-consumer communication. The environmental decelerations are based on LCI (life cycle inventory), LCA (Life Cycle Assessment) or information modules which are verified independently. Moreover, these decelerations can be set by one or several organizations. The decelerations can have different names, for instance environmental product declaration (EPD), eco-profile and Eco-Leaf [47].

The Environmental Product Declaration (EPD) ® is an international system established by an independent organization. This system aims to help the companies in exchanging and comparing verified information regarding the environmental impact of their products. Furthermore, the EPD® system can form environmental declarations based on ISO 14025 [52].

3. IMPLEMENTATION OF CARBON FOOTPRINT

3.1 Life Cycle Assessment

Life Cycle Assessment (LCA) is defined according to ISO 14040 and ISO 14044 Standards as:

"Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle"

Life Cycle Assessment is an environmental tool that has been developed to addressees the environmental aspects and potential environmental impacts during the entire life cycle of a product or a service [21].

There are four stages in the LCA study. The first one is to outline *the goal and scope* of the study which includes the system boundary. The second stage is about *collecting the required data* for the input and output. This step is called *the inventory analysis* (LCI) where the modeling of the study is established. The third stage is the LCIA (life cycle assessment inventory analysis), where the LCI results are evaluated based on available supplementary information in order to recognize their environmental impacts. The final stage is the *interpretation* of LCA. The stage where the conclusion is prepared along with the recommendations according to the goal and scope of the study [21].The LCA stages can be seen in Figure 17.
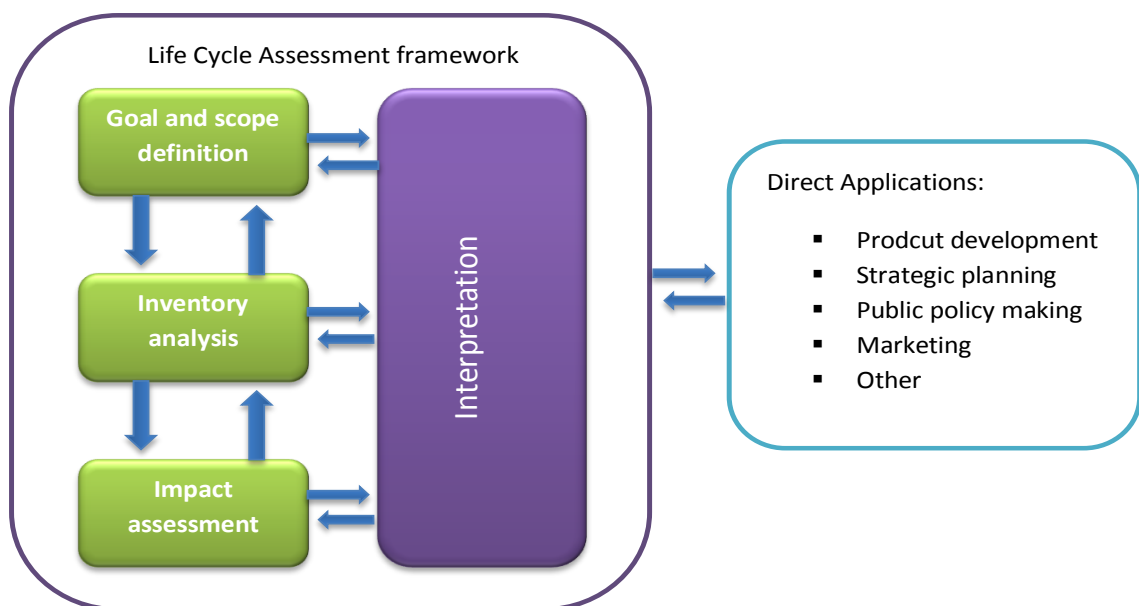
Figure 17. *LCA stages [21].*

For the *Goal and Scope stage* of LCA, there are some aspects that should be considered. The goal part should contain: the intended application, reasons for conducting the study case and the type of audience who are anticipated in this study. If the results will be either open for publicity or in a disclosed form. Additionally, the scope should contain the studied product system, the functional unit, system boundaries as well as the requirements for the data, allocation and type of report format of the study [21].

In order to calculate the related inputs and outputs of a product in the system, the inventory analysis should consist of data collection and quantify procedures. The goal or scope of the study case might change during the process due to the increased knowledge on the system data and may leads to reset the data requirements and limitations [21].

The *LCIA (life cycle inventory analysis)* main objective is to assess the consequence of potential environmental impacts by using the results from the inventory analysis. Figure 18 illustrates the features of the LCIA stage that are involved in the evaluation process [21].
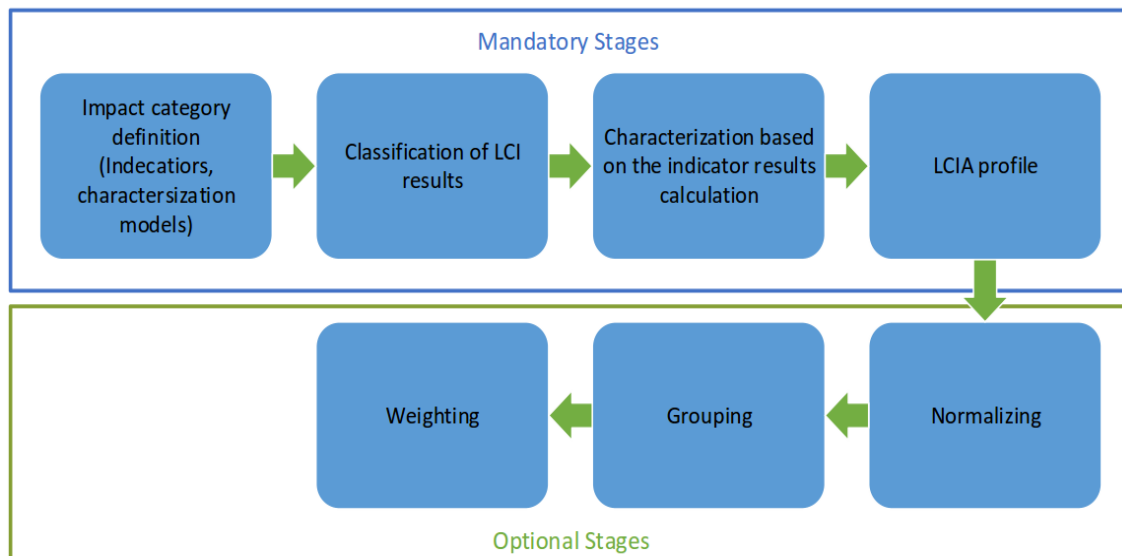
Figure 18. Elements of the LCIA stage [21].

The *impact category* definition is the stage where the selection of indicators and impact category as well as the characterization models is determined in the elements of LCIA. The impact and indicator category are models of cause effect chains and their end-points. The following stage is the *classification* where the results of LCI are allocated to their impact categories. After that the amount of environmental indicators categories is calculated in the *characterization* stage. The final stage in the elements of LCIA is the *LCIA profile*, where all the indicator results for several impact categories are collected. The data about the environmental impacts as results of the input and output of the product can be provided through the LCIA profile. These four stages in LCIA are mandatory elements. However, there are three stages, these stages are optional and can

be done when it is required one scale index. *Normalization* part is the first optional step where the results of the indicator category are converted after being divided by specific reference value. In *grouping*, that is the second stage, where the impact categories are arranged and ranked. Finally, by using numerical factors, the indicator results are transformed and aggregated in the third stage called *weighting* [21][22][53].

The final stage in the LCA is the interpretation, where all of the LCI and LCIA results as well as the outcomes are combined together. The aim is to deliver the results which are expected and mentioned in the goal and scope. Furthermore, the interpretation should include the conclusion, recommendations and also the limitations of the study case. Thus, this stage is offered to deliver readily reasonable, comprehensive and reliable presentation of the findings in life cycle assessment [21].

3.2   From LCA to CF

Carbon footprinting is a simplified analysis tool that represents a subset of Life Cycle Assessment, which focuses only on one impact category [3]. This impact category is the global warming potential indicators (GWP). If the chosen impact category is the greenhouse effect in LCIA then the phases will affect to the phases of LCA. For instance, when setting the goal of LCA of a product is to obtain the greenhouse gas emissions only, the scope of LCA will affect the requirements of the data. The reason behind that are the GHG emissions which were set to achieve without considering the rest of the indicators. However, CF data is more simplified and less complicated compared to LCA data e.g. a product or material can be modeled based on GHG emissions data instead of including more indicators.

3.3   LCA software packages

Recently the LCA tool has extended overall recognition in a varied scope of uses. The scope of uses are such us eco-design, product environmental improvement, environmental labelling and policy evaluation and carbon footprint assessment. Due to the increased recognition of Life Cycle Assessment, software tools and databases were developed in order to execute LCA studies [54].

There are several existing types of LCA software packages that can be implemented to calculate the environmental footprint assessment of a product, and are available in the market for purchasing and licensing. The most widespread and reliable LCA software packages are:

- Umberto NXT LCA
- Sima Pro 8
- Gabi 6 Sustainability Software
- openLCA

The most important factor when choosing a LCA software package is the data including: the quality, accuracy, volume, relevance and the availability of this data for users. Currently, there are two supreme extensive international LCI databases, the "Ecoinvent Database" which is developed by the Swiss Center of Life Cycle Inventories and the "GaBi Database" which is developed by the PE International [61][59]

Each of these softwares mentioned previously uses one or two of the databases (Ecoinvent and Gabi databases). Thus, it is possible to compare the software packages due to their similar goals.

The main function of the LCA software is to achieve mass balances and energy on a product which is identified by the user. Additionally, an LCA software package allows allocating energy uses and emissions on some average basis, generally mass. However, these software packages have their advantages and disadvantages in terms of some specifications. The primary specifications that are used in the comparison [55]:

- Carbon footprint Assessment: CF can be initially determined by the LCA methodology based on the ISO 14044. The software package permit to reveal the carbon footprint, expose the possible ways to decline potentials and highlight harmful adjustments. For instance, relocate environmental burdens from one phase of another life cycle [56].
- Impact Assessment: the impact assessment is considered an important and valuable tool related with LCA software. The software is required to have this specification otherwise the package is basically a database and a spreadsheet.
- Graphical Representation of Results: the main purposes of this specification are focused on the report writing and clarification.
- Sensitivity Analysis: an automatic analysis, it is available in a few software packages and optional. The main purpose is to provide a possibility to model the study in alternative process parameters during the calculations.
- Cost: It is one of the most important factors when choosing a suitable software package.
- Flow Diagrams: the flow diagrams are an essential part of the study, it allows the user to review the indicators that are either involved or eliminated in the system boundaries.
- Limitations on geographic input/output parameters and English language: there are some restrictions on a number of inputs and outputs parameters in LCA software packages which are necessary to form a process. Besides, the compared software packages are from the same European origin, it means that the objects in a process are labeled in the identical language as LCA software origin.

Table 5 demonstrates a comparison of the four common LCA software packages.

Table 5. *Comparison of four available Software packages in the market* *[57][58][59][60][61]*

Software	Umberto NXT LCA	SimaPro	GaBi	openLCA
Language	English, German	English, French, Italian, German, Spanish	English, German	English, German
Supplier	ifu Hamburg GmbH	PRé Consultants B.V.	PE International GmbH University of Stuttgart, LBP-GaBi	GreenDelta
Supports full LCA	Yes	Yes	Yes	Yes
Main database	Ecoinventv 3,3.1; GaBi Databases optional	Ecoinvent v3	Ecoinvent v3,3.1; GaBi Databases	openLCA Database; free available databases, purchase : GaBi, Ecoinvent v3 limited
Carbon footprinting	Yes	Yes	Yes	Yes
Graphical impact assessment	Yes	Yes	Yes	Yes
Sankey (Flow) Diagrams	Yes	Yes	Yes	Yes
Restriction input / output	depending on the license purchased	depending on the license purchased	depending on the license purchased	Yes
Auto sensitivity analysis	Yes	Yes	Yes	Yes
Cost	Quote on request permanent license; Starting From €20000.	Business Licenses: €7000- €16000 Educational Licenses: €2000- €3500	Quote on request Prices are variable and not fixed	Free
free trials Available?	14 days free trail	Demo version	30 days free trail+ free student version	N/A
Export results to MS Excel	Yes	Extra tool package required	Yes	N/A

After comparing the software packages, it is clear that almost all of them have the same basic functions for performing LCA. However, the differences in the packages are only in the method, flexibility, speed and information which are provided by each software package.

The software package used in this thesis was based on three main criteria including cost, carbon footprint assessment and the availability of the tool.

Although, the openLCA tool is completely free software package that contains a main databases. The user must purchase the other important and required databases separately such as ecoinvent v3 and GaBi database.

The only available software package for Tampere university of Technology at Materials Science department is the CES selector by Granta design purchased license in 2015. In order to conduct an LCA study, the software is supplied with additional tool called Eco Audit™.

CES Selector is a PC software that allows product development groups and materials specialists to find, discover and implement materials property data. The software is developed by Granta Design Company which was established in 1994 with Cambridge University. The advantages of this product are the possibility to re-design, replacement of materials, take decisions in early steps of design, review the potential changes in design and provide a full database of different types of materials and provide solutions for problems. The CES selector is supplied with add on tool called Eco Audit™. It allows calculating the embodied energy and CF for the complete life cycle of a product. The Eco Audit™ permits the users or designers to reduce the cost and meet the regulatory requirements of environmental targets. Furthermore, the tool will help in decreasing the environmental impacts of a product as well as reducing the cost of production. Hence, the objective mentioned before will be an essential support for the users to take decisions to consider an eco-design for the product [62].

The methodology of Eco Audit provided by Granta design offers quick estimations in each life cycle phase, the energy consumption and CO_2 emissions. Figure 19 shows the structure of the tool which starts by defining the "Bill of materials" by users as well as providing the process method and shaping processes. Additionally, the secondary processes can be added such as machining, joining and finishing to include specific details of manufacturing. The transportation, use of the product and end-of-life details are provided in the tool from the grant's material universe databases. In these databases, materials, processing and environmental data are provided. According to standards PAS 2050 and ISO 14040, the methodology of Eco Audit and fundamental data are constructed to certify that results are reliable with detailed LCA study cases [62].
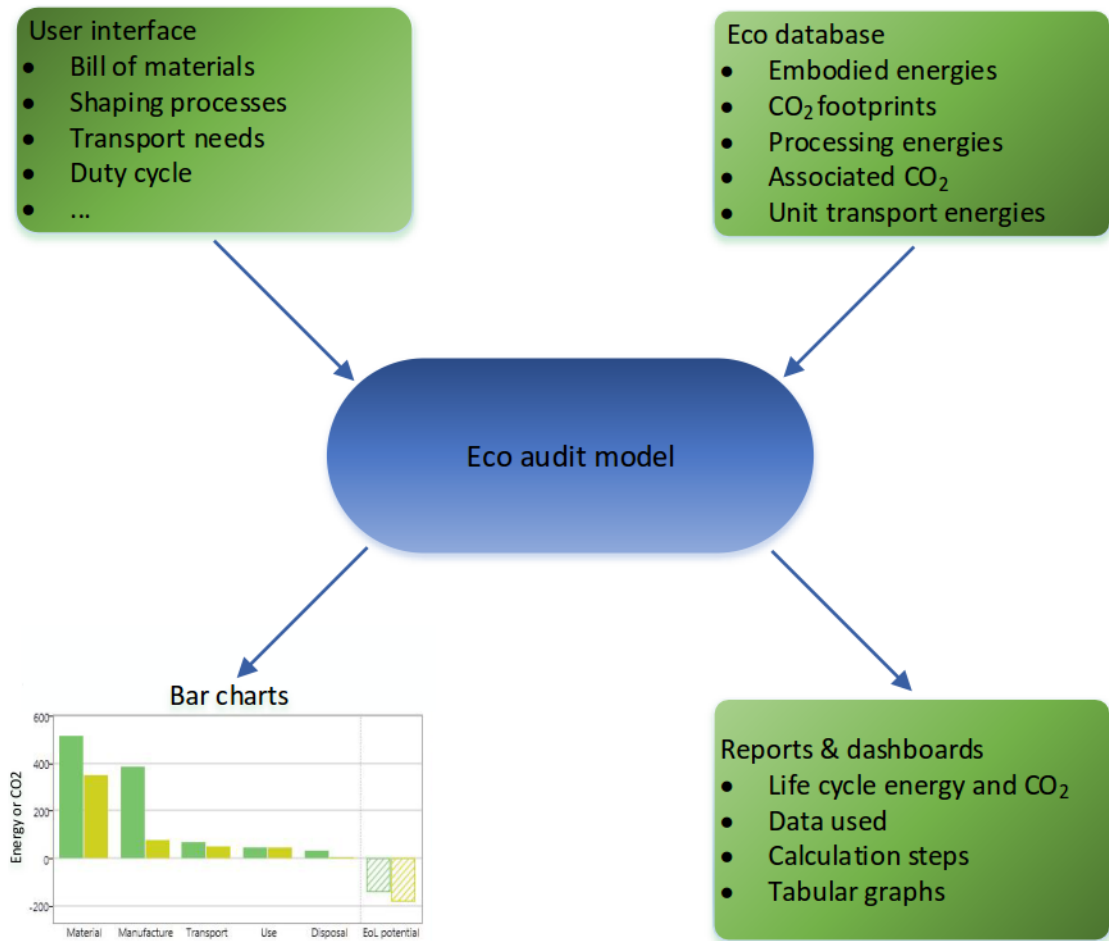
Figure 19. *The structure of Granta's Eco Audit technology* [62].

3.4   Review: LCA of composite materials

There are several LCA studies that have been carried out on specific composites materials. Joshi et al. conducted an LCA study case on natural fiber composites (NFC) and glass fiber reinforced plastics (GFRP). The results of this study show that NFCs are less harmful for the environment in automotive applications. Also the natural fiber composites have similar components to GFRP in terms of service life [65].

Moreover, Duflou et al. have applied LCA method to define the environmental impact of carbon fiber reinforced composites (CFRP) in vehicle manufacturing. The results of the study showed the advantages of using CFRP in fuel savings through the use phase of the vehicle. Also, the life cycle of the vehicle increased for almost 132.000 km [66].

Song et al. have investigated the energy used in the LCA of composite materials manufactured by pultrusion process. Several types of analysis processes including process analysis and economic input-output analysis were used in the study. The amount of energy used for producing automotive products was compared with conventional materials such as steel. Hybrid analysis was used for the pultrusion

process of the automotive applications. The results of the study show the advantages of using the composites materials in the use phase of the automotive applications [67].

Furthermore, several studies exist about combining cost and environmental of materials assessment in an automotive industry. Ungureanu et al. established a sustainable model in order to execute such an assessment. In this study, the composite materials were not deliberated instead, aluminium was investigated and compared with steel for a Body in White (BIW). The environmental impacts with costs were estimated through the life cycle of the body structure and the manufacturing costs were calculated based on cost modeling. The entire amounts of fuel used through the life cycle of a vehicle were used to estimate the fuel costs in the use phase. The carbon footprint (CO_2) was used as an indicator to carry out the environmental assessment. However, the disadvantage of this project is that the other important environmental indicators involving resources and ecosystem were not included [68].

Roes et al. have compared polypropylene nano-composites to steel by using environmental and cost assessment for an automotive panel [69]. The part weight equivalence was measured by using Ashby material indices [70]. Based on ISO, the LCA was accomplished. Lloyd and Lave and Song et al. have investigated environmental and economic effects of materials replacement with composite materials. Lloyd and Lave have studied the possibility to exchange nano-clay reinforced composites and aluminium with steel in light duty body panels [71]. Moreover, Song et al. compared extruded carbon fiber parts in trucks and buses [67].

3.5   Environmental analysis of pultruded products

Based on the green guide to composite materials by NetComposite, the production steps of the composite products are analyzed into different manufacturing steps [72]. The steps of pultruded composite products are illustrated in Figure 20 based on the LCA framework. The total environmental impact is measured from each step of the production method.

The first step in analyzing the pultrusion process is the matrix and fiber materials, which are polyester and glass fibers. The polyester resin is produced by polymers and other materials such as filler, accelerator and catalyst. The high environmental impact associated with the resins raw materials extraction and production is due to high amount of fossil fuels involved in the polymers production. For the glass fiber, the environmental impact depends on the amount of energy required to produce a different types of fibers. In order to deliver a good surface finish to the final product, gelcoats are frequently applied in the composite manufacturing. These gelcoats consist of resin and fillers and can be applied on surface by roller, brush and spray [72].
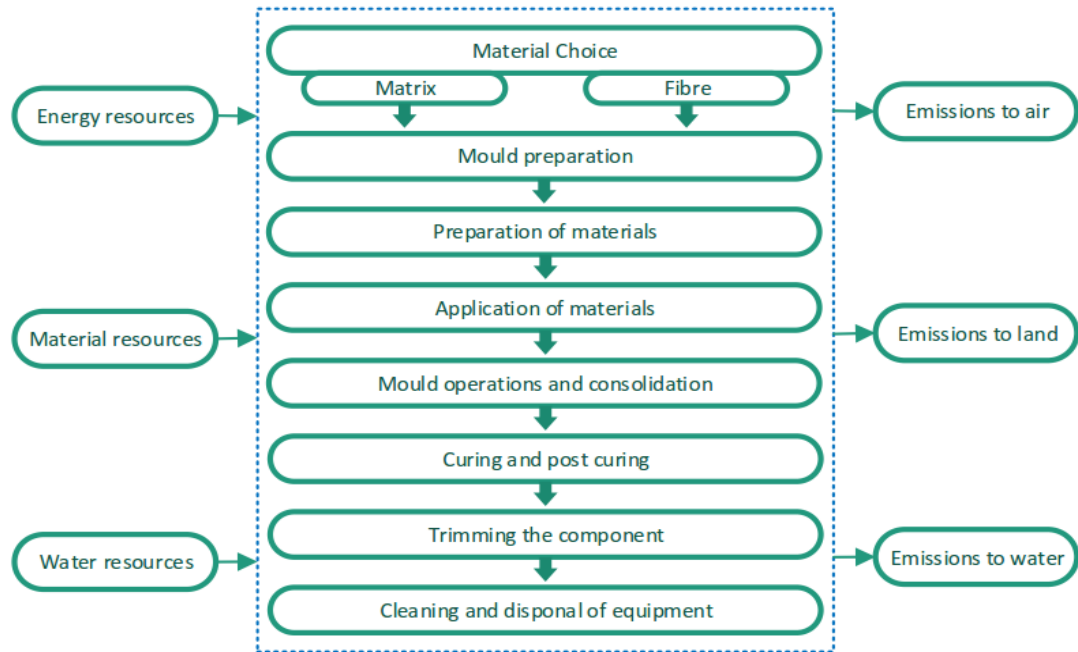
Figure 20. *Production steps of composites products [72].*

The second stage is the materials preparation for matrix and fibers. The preparations are consisting of the resin mixing and cutting of the fibers. During the mixing and application of the resin, the most significant emissions impacts are generated from the styrene that is used in the polyester resin. The closed mixing of the resin can prevent the emissions of styrene. The fibers preparation has a lower environment effect of 1% less than the other steps. The step where the resin is applied in the pultrusion process, involves a high amount of styrene emissions emitted due to the resin bath that is required to cover a large surface area [72].

The mould preparation, curing, trimming and cutting steps in this process, are considered to contribute less than 1% of the total impact of the process. Moreover, the cleaning step of equipment in the pultrusion process, including the use of acetone and glycol ether were found to have less than 1% of the total pultrusion process emissions [72].

An example from NetComposite website is used to illustrate the impact of the pultrusion process. The example is a 1m x 8m panel sandwich structure and the core here is ribs instead of core materials. The composition of the panel is 60% volume fraction of polyester resin, 50% $CaCO_3$ filler, 40% volume fraction of woven glass mat and glass rovings. The processes applied in this case are: closed mixing of resin bath, consolidation through die, curing in the heated die, cutting by saw and cleaning the equipment. Figure 21 shows the emissions impacts aroused from the production of the panel [72].
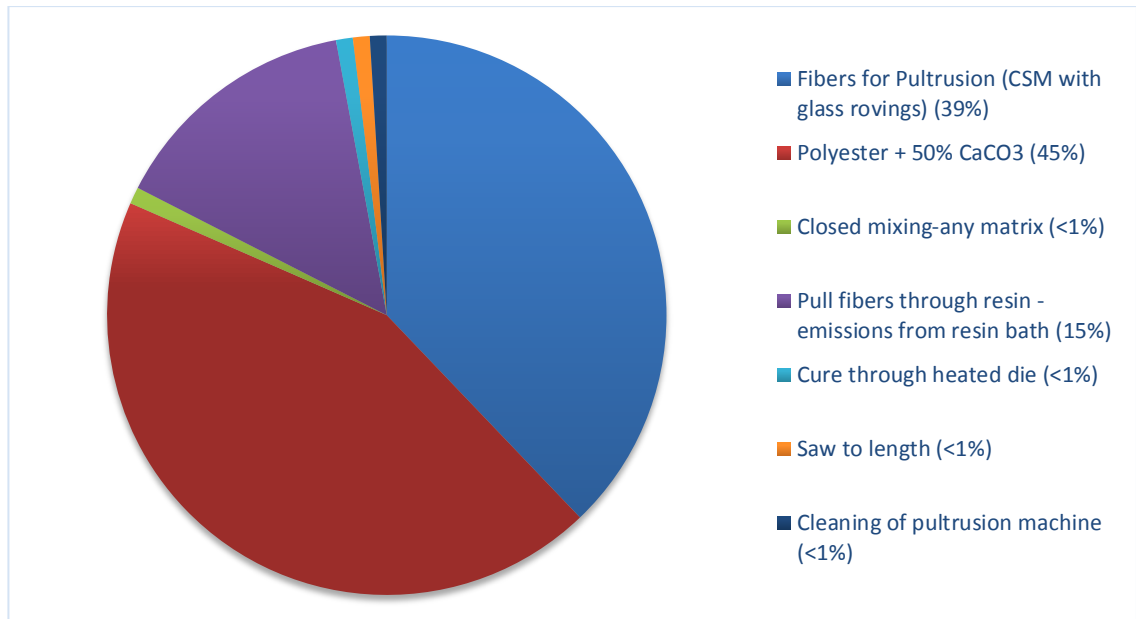
Figure 21. *Pultrusion process breakdown impacts of making 1 m² double curvature panel [72].*

Overall, the pultrusion process, especially the use of glass fibers and polyester shows a lower rating of environmental impact. However, the pultrusion's major environmental impacts ascend from the resin emissions and in particularly the resin bath.

4. CASE STUDY: SIDE PANEL OF A COACH

4.1 Body panel description

A body component of a vehicle situated at the side of a coach is considered for a weight reduction through adequate materials replacement. The side panel is thin rectangular plate with a dimension of 10000mm in length and 920 mm in height with a variable thickness based on the materials. Additionally, the side panel should resist corrosion, wear and should be light weight. In this study, the light materials used are made of a combination of unsaturated polyester resin (UP) filled with glass fiber GF 43.2 wt. % (percentage by weight), unidirectional fiber (UD) and chopped strand mat CSM. The pultrusion process is selected as a composite manufacturing technique which is known as the most energy efficient and cost effective due to high production and automated rate.

The main purpose of this study is to show the environmental impact of the composite material mentioned before and compare it with other conventional materials such as galvanized steel, stainless steel and aluminium, in terms of environmental impact. The various materials used for the comparison and their detailed properties are shown in Table 6.

In this study, the pultruded composite panel (GF/UP) is manufactured by Exel Composites Company (Finland) which is one of the world leading companies in composite production and especially in the pultrusion process [83].

Table 6. *Materials descriptions, properties and component weight of the side panel*

Materials	Thickness (mm)	Density (kg/m^3)	Weight (kg)
Stainless steel, ferritic, AISI 405, wrought, annealed, low nickel	0.9	7.82×10^3	64.74
Aluminium, 5005, wrought, H14	2.5	2.72×10^3	62.56
Carbon steel, AISI 1015, annealed	0.75	7.9×10^3	54.51
E-glass fiber/polyester, pultruded composite profile (UD fiber and CSM) 90° direction	3	1.9×10^3	52.44

4.2   Scope definition

4.2.1   Functional Unit:

According to PAS 2050 [7], the functional unit is defined as "the quantified performance of a product system for use as a reference unit in a life cycle assessment study". In this case is the weight of body panel component that is located on the side of a coach, is referred as a functional unit. The panel dimensions are, 920 mm in height, the length for one side is 10000mm and the thickness depends on the materials used as shown in Table 6. In addition, the different weights of the component based on the materials are also stated in Table 6. The body panel is fixed in a visible area on the side of the coach thus; the materials should fulfill a high standard of surface quality, corrosion resistant and very good adhesion properties. Figure 22 a, shows an example photo of component assembled to a coach and Figure 22 b and c, illustrate a drawing (front and back) of the component designed on Solidworks software.
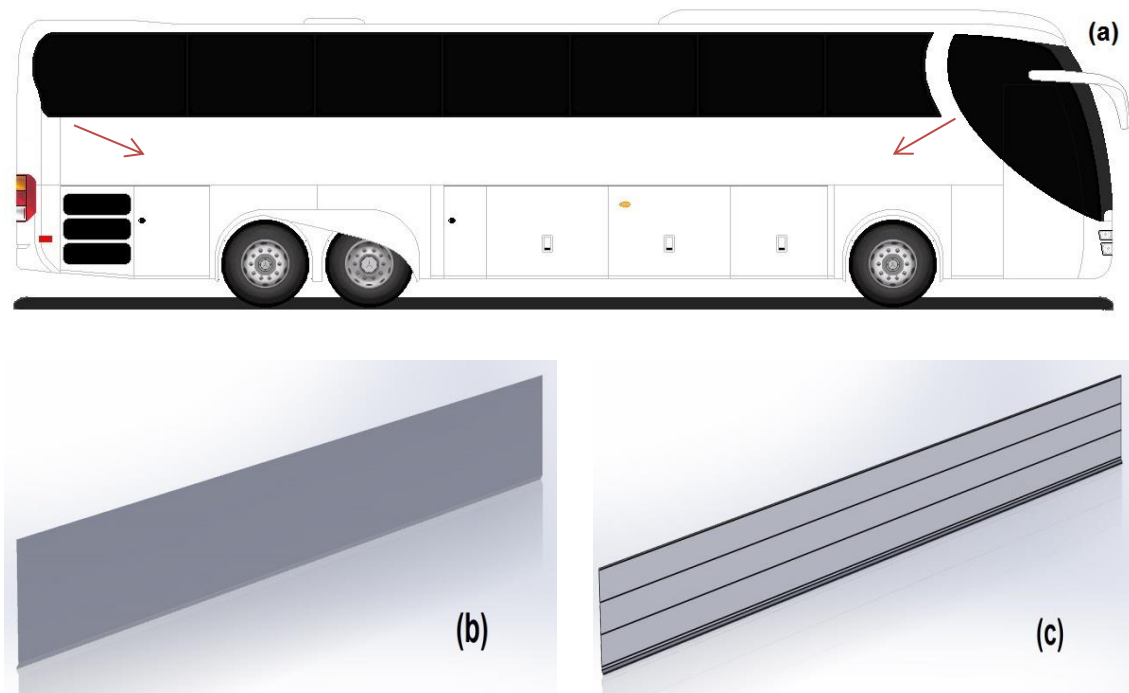
Figure 22. *The body component fixed on a coach (a), Solidworks drawing of the component (b) front and (c) back.*

4.2.2   System Boundary

The system boundary for the CF of a product should contain all the stages that are incorporated into the system. As well as the description of the elementary flows: inputs and outputs should be involved in the assessment (e.g. material or energy consumed in each process). In this study, the scope of the product is considered for the complete life

cycle of the coach body component which expands from cradle to grave. The life cycle stages of the coach body panel consist of the following stages:

1. Raw materials extraction
2. Manufacturing of the body components
3. Transportation or distribution to customers
4. Use of the product
5. Disposal or end-of-life

The product system boundaries of the glass fiber/unsaturated polyester resin product as well as the other conventional materials are displayed in Figure 23 and followed by detailed description.
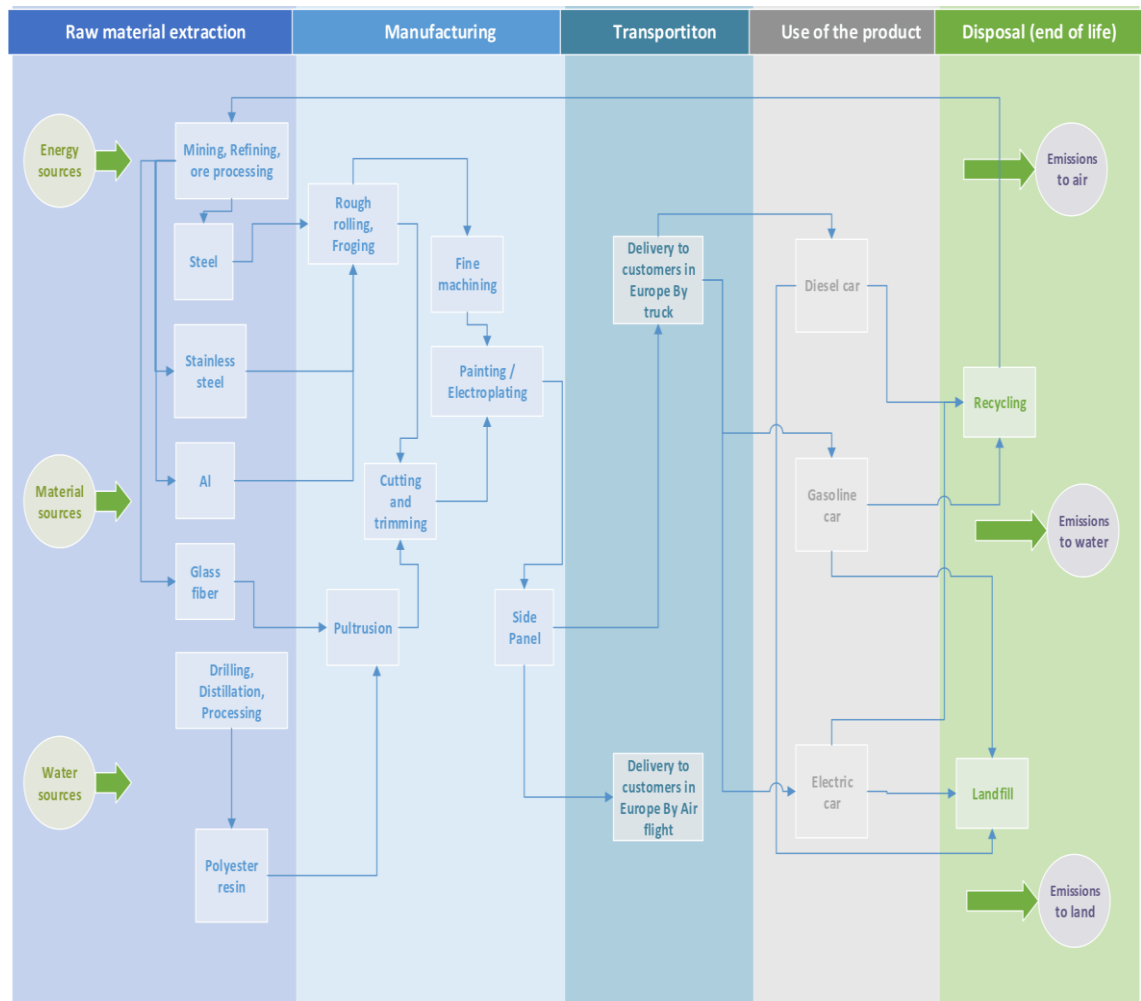
Figure 23. *Detailed Life Cycle Assessment of the materials used, manufacturing processes, transportation scenarios, product employment scenarios and end-of-life.*

1. Raw materials extraction:

The first stage in the life cycle of a product involves the raw materials and extraction. For the composite product case, the material extraction of glass fiber E-grade occurs by pulling fossil fuels from the earth then refining and separating these materials, which is

followed by the production of materials. The UP resin is produced by chemical process. Whereas for the steel, stainless steel and aluminium, the production of such a materials starts from ore mining then refining of the materials and finally the primary production of those materials.

2. Manufacturing of the component:

GF/UP component is manufactured through the pulturison process at Exel Composites Company [83]. This process involves the impregnation of the 43.2 wt. % of GF and unsaturated polyester resin in a bath and then pulling them over a heated die. The curing takes place within the heated die before leaving the die as a final finished profile. The final stage in the process is the cutting and trimming of the profile in order to obtain the required length that results in waste for approximately 2% of the materials. As for the aluminium, stainless steel and steel components, they are manufactured from rough rolling, forging materials which are supplied as a coil. In order to finalize the metal product appearance, there are several secondary processes used such as fine machining and grinding. This might result in a higher material loss of approximately 5%.

3. Transportation or Distribution:

This stage is where the component is distributed to customers in the market. In this case, the body part is delivered to several customers around Europe by either trucks or air flights. The distance from factory to customers varies from 1500 to 3000 km.

4. The usage stage:

This phase indicates the use of the product as a part of the vehicle which is considered as a mobile mode. Based on the U.S federal transit administration, the product life is estimated for 12 years of use as well as for a driving distance of 200 km per day and for 350 days usage per year [73]. Due to limited source available of the databases in the CES software, three types of fuel and mobility were used in the case including: diesel-heavy goods vehicle, gasoline-family car, electric-family car.

5. Disposal or end-of-life:

The GF/UP component disposal route is considered to be discarded in a landfill. While, the other metal materials disposal route is recycling of the body component. The recycling fraction in the current supply is varied for the other materials between 35-44% [62].

4.3   Methodology

4.3.1   Data collection

Each life cycle stage has different influence on the final total emissions. The detailed data in this study contain all greenhouse gas (GHG) emissions and energy consumed within the boundary of the product. In addition to the data source, information about the data quality is presented and some suggestions to improve the quality for the future use. All the emissions and calculation factors were collected from the Granta design database [62] including all, primary data for materials, secondary data for the processes, energy, water usage and recycling data.

1.   **Raw material data**

The concept of *embodied energy* is applied in the case which refers to the amount of energy used in order to extract process and refine the material before using them in manufacturing. The embodied energy is measured in MJ/kg [74]. All the primary production data including energy consumption and CF of the materials were collected from the Granta design databases based on several suppliers [62]. Furthermore, the CF emissions generated from the raw materials phase are calculated by the amount of material used and the emission factors from the software. Table 7 below presents the embodied energy, CO_2 emissions and water usage used for the primary production of each material.

Table 7. *Raw materials extraction data from CES selector software (Eco-Audit) by Granta design company [62].*

Material	Embodied energy, primary production (MJ/kg)	CO_2 footprint, primary production (kg/kg)	Water usage (l/kg)
Stainless steel	*43.3-47,7	*3.49-3.85	*99,3-110
Aluminium	*190-209	*12.5-13.8	*1.14×10^3-1.26×10^3
Carbon steel	30.8-33.9	2.26-2.49	*43.2-47.7
pultruded composite	*87-95.9	*4.56-5.02	*231-255

* Estimated values from the databases.

In order to enhance the quality of the data, it is required to set up a cradle-to-gate inventory data of each material from their manufacturers. Although the data presented here is based on an industrial average estimations and the credibility of the information might be low in comparison with an own designed cradle-to-gate inventory.

2. Manufacturing of the component data

The GHG emissions resulting from the manufacturing phase are determined by specific values for the primary processes and the secondary processes. Moreover, the four types of materials that have been studied are considered to be virgin materials (no recycled materials). The primary processes used in this study are: i) pultrusion process, ii) rough rolling, and iii) forging process. The available values for the energy consumption and CO_2 emissions are estimated and collected from different manufactures [62].

Furthermore, the secondary processes that have been reviewed in the case are i) cutting and trimming, and ii) fine machining which outcomes in low emissions compared to the primary processes.

Finally, the finishing processes data were included in the calculations such as painting and electroplating. Those processes consume a high amount of energy of (12 MJ/m^2 and 89 MJ/m^2 for painting and electroplating respectively). The CO_2 emissions are 0.98 per m^2 and 4.8 per m^2 for painting and electroplating respectively. Based on the available databases, the energy consumption and CO_2 footprint were used to calculate the total emissions and energy. Table 8 presents the processes energy and the corresponding CO_2 emissions [62]. *The possible approach to improve the quality of the data is by setting up a cradle to gate inventory for each process based on their specific manufacturers.*

Table 8. *Manufacturing processes data collected from CES selector software (Eco-Audit) by Granta design [62].*

Material	Primary process	*Energy (MJ/kg)	*CO_2 footprint (kg/kg)	Secondary process	*Energy (MJ/kg)	*CO_2 footprint (kg/kg)	Finishing process
Stainless steel	Rough rolling, forging	2.06-2.28	0.155-0.171	Fine machining	3.14-3.47	0.235-0.26	Painting
Aluminium	Rough rolling, forging	3.7-4.08	0.277-0.306	Cutting and trimming	0.3	0.023	Painting
Carbon steel	Rough rolling, forging	2.57-2.84	0.193-0.213	Fine machining	3.9-4.32	0.293-0.324	Electroplating Painting
pultruded composite	Pultrusion	2.95-3.26	0.236-0.261	Cutting and trimming	0.3	0.023	Painting

* Estimated values from the databases.

3. Transportation data

For the transportation phase, the GHG emissions are produced from the distribution of the product from the manufacturer to the customers. In this study, there are two scenarios of transportation types and the associated fuel used in the distribution. The first case scenario is a 32 tonne truck using diesel fuel. The second case scenario is a short haul aircraft using kerosene fuel. Based on the criteria of travel distance and transport, fuel type, the total amount of energy and CF can be calculated. The possible approach to improve the data quality is by quantifying the fuel consumption of the vehicle during the distribution process. As well as a proper emission factor presented by the vehicle manufacturer (CO_2 kg per gallon fuel) will result in a higher data quality. Table 9 shows the first case with the distance, energy and CO_2 emissions considered in this study. Where, Table 10 shows the second case scenario with the distance, energy and CO_2 emission values.

Table 9. Transportation data used for the truck-diesel type (first case Scenario) taken from CES selector software (Eco-Audit) by Granta design [62].

Stage Name	Transport Type and fuel	Distance (km)	Energy (MJ/metric ton.km)	Carbon footprint (kg CO_2/metric ton.km)
Transport from Factory to customers 1 (Europe)	32 tonne truck-Diesel	3000	0.94	0.071
Transport from Factory to customers 2 (Europe)	14 tonne truck-Diesel	1500	1.5	0.071

Table 10. Transportation data used for the air flight-kerosene type (second case Scenario) taken from CES selector software (Eco-Audit) by Granta design [62].

Stage Name	Transport Type and fuel	Distance (km)	Energy (MJ/metric ton.km)	Carbon footprint (kg CO_2/metric ton.km)
Transport from Factory to customers 1 (Europe)	Short haul aircraft-Kerosene	3000	6.5	0.45
Transport from Factory to customers 2 (Europe)	Short haul aircraft-Kerosene	1500	11-15	0.76

4. Use of the product data

In the usage phase, the product is considered to be fixed as a body part on a coach. It should be mentioned that, the materials choice has a significant effect on the total body mass, energy and CO_2 emissions by the vehicle through its operation. The CF emissions and energy used are determined through the vehicle and fuel type as well as the product

life and distance. There are three scenario cases that have been studied: a) family car-diesel, b) family car-gasoline and c) family car-electric. The data of the product life, distance per day and usage per year were collected based on the U.S federal transit administration report [73]. Whereas the factor values for energy and CF emissions were taken from CES selector databases. The data quality of this phase can be enriched as mentioned before during the raw materials phase and manufacturing phase. Table 11 indicates the three case scenarios with the fuel type and mobility type, location of the product use, distance and CO_2 emissions and energy consumption.

Table 11. *The usage phase data of three scenarios of energy used in the vehicles (diesel, gasoline, electric) and CO_2 footprint obtained from CES selector software (Eco-Audit) by Granta design [62].*

Case Scenarios	First Scenario	Second scenario	Thrid scenario
Fuel and mobility type	Diesel-family car	Gasoline-family car	Electric-family car
Use location	Europe	Europe	Europe
Energy Consumption (MJ/tonne.km)	0.90	2.1	0.17
CO_2 Emission (kg/MJ)	0.071	0.071	*Country specific
Distance (km per day)	200	200	200
Usage (days per year)	350	350	350
Product life (years)	12	12	12

* Country specific: The data has been calculated based on location 'Europe'. The CO_2 footprint [kg/MJ] generated from electricity by fossil fuels can be calculated based on equation (1):

$$CO_2 \text{ footprint} = \frac{\text{Fossil fuel proportion}}{\text{Conversion efficiency}} \times CO_2 \text{conversion factor } (\frac{\text{kg}}{\text{MJ}}) (1)$$

5. End of life data

The GHG emissions generated from the end-of-life phase can be measured by recycling the metal materials. Whereas, the recycle fraction of the composite materials in current supply is currently low [74]. Thus, the composites products with their long life span are discarded at certain stage in a landfill. The recycling process energy and CO_2 emissions which are estimated based on the amount of material processed and certain emission factors. Table 12 presents the embodied energy required to recycle each material and CF of the recycling process.

Table 12. The disposal route data for each product collected from CES selector (Eco-Audit) by Granta design [62].

Materials	Disposal route	Recycle fraction in current supply (%)	*Embodied energy, recycling (MJ/kg)	*CO_2 footprint, recycling (kg/kg)
Stainless steel panel	Recycle	35	10.5-11.6	0.824-0.911
Aluminium panel	Recycle	44	32.3-35.7	2.54-2.8
Carbon steel panel	Recycle	42	8.1-8.96	0.636-0.703
pultruded composite panel	Landfill	<1	N/A	N/A

* Estimated values from the databases.

4.3.2 CF calculations

The entire life cycle for the body component of a coach is modeled by using CES selector software (Eco Audit) [62]. According to PAS 2050, the CF of activity can be measured by multiplying the activity data (e.g., kg mass materials consumed) by the emission factor of this activity (e.g., kg CO_2e per kg materials). By summing all the CF activities during the complete life cycle of the product, the total amount of carbon footprint can estimated as defined in equation (2) [7]:

$$\text{Total CF of the prodcut (kg)} = \sum \text{Activity data} \times \text{activity emission factor} \quad (2)$$

The energy usage and CO_2 footprint values from Table 9and Table 10 are used with the distance and the product mass, to determine the environmental impact of the transportation phase for both case scenarios. The equations (3) and (4) are applied [74]:

$$\text{Transport energy (MJ)} = \text{transport energy per unit mass \& distance (MJ/tonne/km)} \times \text{distance (km)} \times \text{product mass (kg)} \quad (3)$$

$$\text{Transport } CO_2 \text{ (kg)} = \text{transport energy per unit mass \& distance(MJ/tonne/km)} \times \text{distance (km)} \times \text{product mass (kg)} \times CO_2 \text{ footprint source (kg/MJ)} \quad (4)$$

In order to determine the environmental impacts associated with the transportation and fuel type used. From Table 11 energy used, CO_2 footprint, product life cycle, distance per day and usage days per year values were applied to the equations below to estimate the mobile use [74]:

$$\text{Mobile use energy (MJ)} = \text{transport energy per unit mass\&distance (MJ/tonne.kg)} \times \text{life distance} \times \text{mass (kg)} \times \text{energy equivalence (MJ/MJ)} \quad (5)$$

$$\text{Mobile use } CO_2(\text{kg}) = \text{transport energy per unit mass\&distance (MJ/tonne.kg)} \times \text{life distance} \times \text{mass (kg)} \times CO_2 \text{footprint source (kg/MJ)} \quad (6)$$

Where the life distance 840000 km is calculated for a coach based on equation (7)

$$\text{Life distance} = \text{product life(years)} \times \text{days per year} \times \text{distance per day (km/day)} \quad (7)$$

5. RESULTS AND DISCUSSION

The employed Eco audit model provides outputs of cradle–to-grave, these including information about the raw materials, manufacturing, transportations, uses of the product and finally end-of-life. Moreover, the calculation of the energy used and CO_2 footprint emissions are obtained from this model. The contribution of the life cycle phases to the total energy consumption and CO_2 footprint are shown in Figure 24 and Figure 25 respectively.

Energy Consumption (MJ)

	Raw materials extraction	Manufacturing	Transportation	Use of the product	End-of-life
Composite	9680	991	278	141000	21
Aluminium	25100	944	332	168000	53
Stainless steel	5970	760	344	174000	49
Steel	3530	4050	286	145000	45
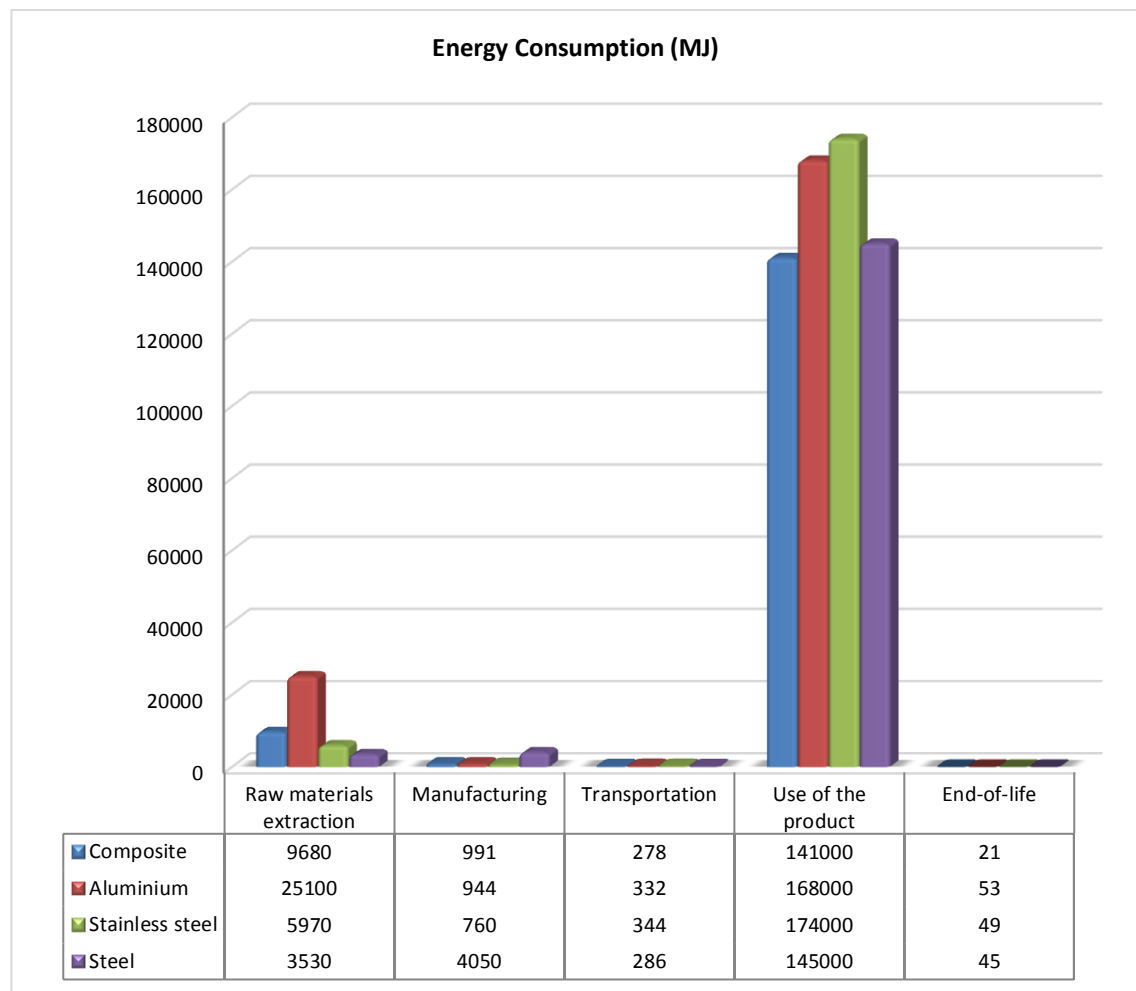
Figure 24. *Total life cycle analysis of the energy consumption values for four different materials: composite, aluminium, stainless steel and steel products.*
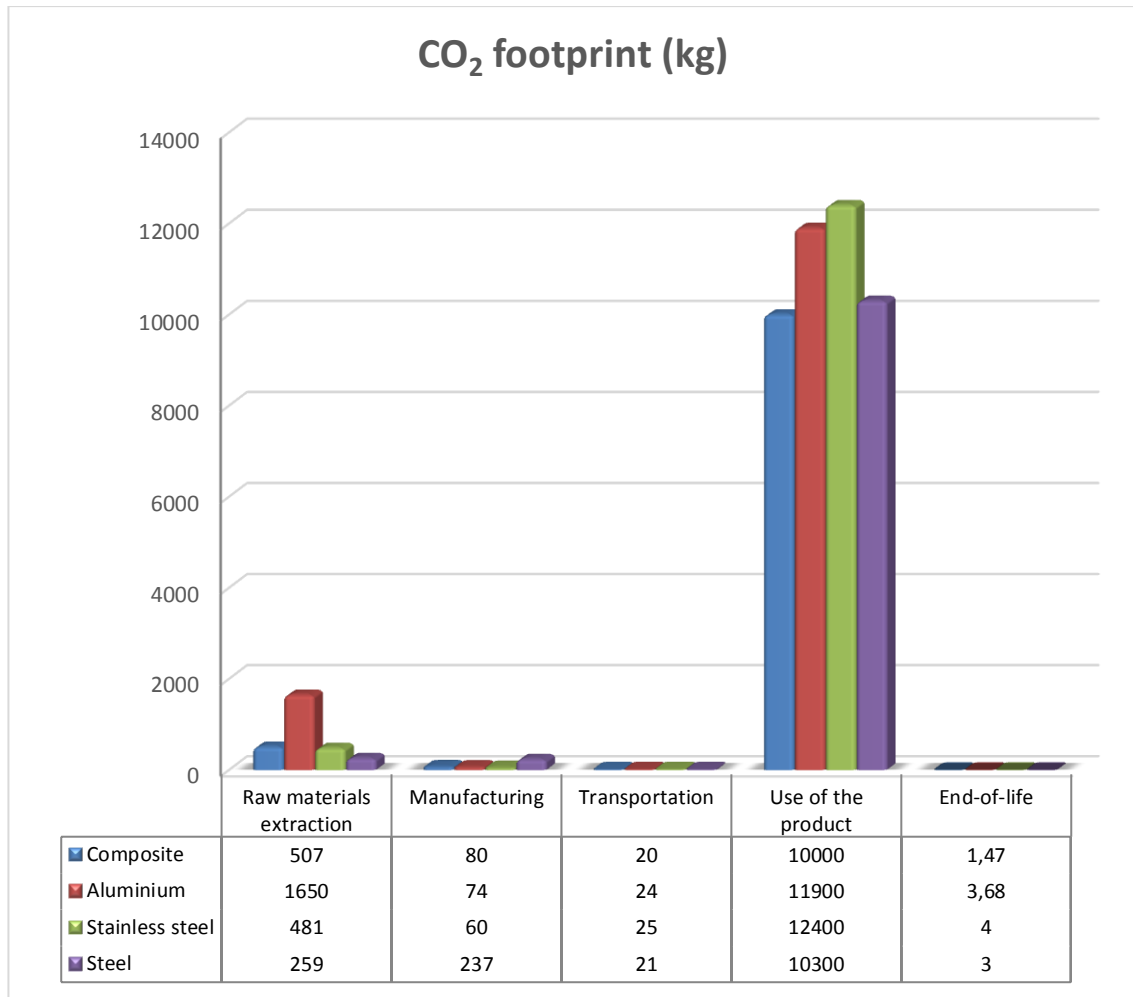
Figure 25. *Total life cycle analysis of the CO_2 footprint values for four different materials composite, aluminium, stainless steel and steel products.*

Detailed breakdown of individual life phases results:

For the raw materials extraction phase, the figures illustrate the amount of energy consumed to produce the aluminium raw materials, which is 2.51×10^4 MJ. This value represents 12.9% of the total energy used during the aluminium panel life cycle. Additionally, the CO_2 footprint emissions emitted during this phase for the aluminium panel is 1650 kg, which embodies 12.1% of the total environmental impact. The high values that are obtained in the aluminium raw material are due to the great amount of embodied energy required to produce the primary materials. A study from the aluminium association in North America shows that more than 60% of the environmental impacts are linked to energy [75]. Especially the use of fossil fuel in production shares the largest attribution of the total CO_2 footprint. Interestingly, the energy to produce the composite panel is 9.68×10^3 MJ and which is about 6.4% of the total energy consumed during the life cycle of the product. The CO_2 footprint emissions generated during the raw materials phase is 507 kg which represents 4.8% of the total environmental impact of the composite panel. The high values of the composite material

are due to a great quantity of embodied energy involving the extraction of the raw materials from minerals, refining and processing of the glass fiber. Additionally, the extraction from fossil fuels and chemical processing of the polyester resin requires intensive energy [67]. In overall, the embodied impacts of the aluminium and composite material inputs are the largest contributors to the total impacts. Table 13 below displays the total amount of energy used to produce each mass of the materials and the CO_2 footprint generated from the production.

Table 13. *The embodied energy and CO_2 footprint for raw materials extraction*

Side panel materials	Part mass (kg)	Quantity	Energy (MJ)	CO_2 footprint (kg)
Stainless steel	64.74	2	5.97×10^3	481
Aluminium	62.56	2	2.51×10^4	1.65×10^3
Carbon steel	54.51	2	3.53×10^3	259
Pultruded composite	52.44	2	9.68×10^3	507

In the manufacturing phase, the steel panel shows a high amount of energy used in comparison to composite panel. The energy consumption in this phase for the steel product is 4.05×10^3 MJ and the CO_2 footprint is 237 kg. The high amount of energy consumed in the steel panel production is due to the secondary processes, including electroplating and painting [76]. These processes require great energy consumption and result in high CO_2 footprint emissions impact. The secondary process contributes for approximately 80% of total energy and impacts. Table 14 shows the detailed values obtained for energy use and CO_2 emissions through each process.

The pultruded composite panel production, the energy required is relatively low and similar to rough rolling and forging process. Whereas, the finishing processes such as painting consumes a large amount of energy with 60% of the total production energy [67]. As mentioned in the environmental analysis of pultruded products, the highest environmental impact occurs in the resin bath and emissions from the polyester resin [72]. However, these values have a minor contribution to the total environmental impacts that are less than 3%. The values for the composite panel, which have less than 1% effect on the total environmental impact.

Table 14. *List of processes used in the manufacturing with energy used and CO_2 footprint*

Side panel materials	Processes used	Amount processed	Energy (MJ)	CO_2 footprint (kg)
Stainless steel	Rough rolling, forging	129.48 kg	300	22
	Fine machining	6.8 kg	23	1.9
	Painting	37 m²	440	36
Aluminium	Rough rolling, forging	125.12 kg	503	38
	Cutting and trimming	3.9 kg	1.4	0,089
	Painting	37 m²	440	36
Carbon steel	Rough rolling, forging	109.02	300	20
	Fine machining	5.7 kg	23	1.7
	Painting	37 m²	440	36
	Electroplating	37 m²	3300	180
Pultruded composite	Pultrusion	104.88	331	26.4
	Cutting and trimming	1.1 kg	0.32	0.024
	Painting	55 m²	660	54

The transportation of the products to the customers in Europe by using a diesel truck was found to create a negligible contribution for the four types of materials products. Table 15 shows the amount of energy consumed and CO_2 emissions generated during transportation of the products. The values are obtained from equations (3) and (4). The values are less than 1% for both energy and CF on the total impact of the products. It should be noted that these figures do not comprise the raw materials transportation to the factory. The weight of the product shows an important effect on the energy consumption, fuel use and environmental impacts. Thus, the pultruded composite panel lower weight leads to less impact from transportations.

Table 15. *The estimation values of energy use and CO_2 footprint obtained from the transportation phase*

Side panel materials	Distance (km)	Product mass (kg)	Energy (MJ)	CO_2 footprint (kg)
Stainless steel	4500	129.48	344	24.4
Aluminium	4500	125.12	332	23.6
Carbon steel	4500	109.02	286	20.3
Pultruded composite	4500	104.88	278	19.8

The use of the product phase, characterizes the operation of the coach after the assembly of the side panel. In this case, the vehicle is considered as a family car operated by diesel fuel for a total life distance of 840000 km for 12 years. The mobile use of the panel for both energy consumption and CF emissions were calculated based on equation (5) and (6). The use phase here demands a range of 92-96% for both energy consumption and CF emissions of the whole life cycle of automobile due to the total amount of fuel consumed. The amount of energy used for the stainless steel panel in the vehicle is 1.74×10^5 M. The use phase is obviously dominating and accounts for 96% of the entire life cycle energy of this product as can be observed from Figure 24. Also the quantity of CO_2 footprint emitted from the use of this product is 1.24×10^4 kg that expresses 96.5 % of the complete life cycle emissions of the product. Figure 25 shows the values of CF produced from the use phase. The weight of the component has a significant effect on the vehicle, which could lead to a higher amount of fuel used and greater values of CO_2 emitted. The aluminium panel comes in second place with high amount of energy use (1.68×10^5 MJ) as well as CF emissions of 1.19×10^4 kg. Whereas the composite panel shows the least amount of energy consumption during this phase with 1.41×10^5 MJ, which represents a 92% of the total energy used for the product. Additionally, the CO_2 emissions generated in the use are 1×10^4 kg, which is about 94% of the total environmental impact. Table 16 displays the total amount of energy consumed and CF emissions during the use phase.

Table 16. *The usage phase energy and CO_2 emissions values of the product as a part of diesel family-car*

Side panel materials	Product mass (kg)	Energy consumption (MJ)	CO_2 footprint (kg)
Stainless steel	129.48	1.74×10^5	1.24×10^4
Aluminium	125.12	1.68×10^5	1.19×10^4
Carbon steel	109.02	1.45×10^5	1.03×10^4
Pultruded composite	104.88	1.41×10^5	1×10^4

The maintenance or the replacement of the side panel was not included in this study case. For the composite materials the maintenance tends to be very rare due to the fact of the long life span of these types of materials. For the other conventional materials such as steel, the maintenance is required when the panel gets wrecked or scratched. However, the replacement of damaged panels with new ones will increase the energy consumption and CO_2 footprint and consequently this would lead to higher environmental impacts [76]. Several studies suggest that the maintenance energy consumed can be disregarded as it contributes for a non-significant share of LCA [77].

As Figure 24 and Figure 25 respectively, show that the use phase has a major role affecting the total environmental impacts of the studied products. The most significant influence in this case was the weight reduction of the panel by replacing the

conventional materials with composite materials. The weight of the panel affects the energy usage that leads to a less fuel consumption and lower amounts of emissions.

In the final phase, end-of-life, for the composite material the side panel of a coach is considered to be disposed in the designated area of the landfill. The other conventional materials are considered to be partially recycled. This phase is a minor contributor for the composites material in both energy usage and CO_2 emissions. The values represent less than 1% of the total impacts of the product life cycle due to the long life cycle of the materials. Whereas, the other conventional materials show slightly higher amount of energy used in the recycling.

Table 17 shows the total values of energy consumption for the materials during the life cycle and also the amount of CO_2 emissions associated.

***Table 17.** Total amounts of both energy and CF of the materials in the life cycle*

Material	Total energy consumption (MJ)	Total CO_2 footprint (kg)
Stainless steel side panel	1.81 x 105	1.29 x 104
Aluminium side panel	1.95 x 105	1.37 x 104
Carbon steel panel	1.53 x 105	1.08x 104
Pultruded composite side panel	1.52 x 105	1.06 x 104

Figure 26 shows the equivalent annual environmental burden (averaged over 12 year of a product life). The composite panel shows the least average values of annual environmental burden of energy use and CO_2 footprint over a year. While the aluminium and stainless steel panels share the highest average values of energy consumption and environmental impacts over a year.
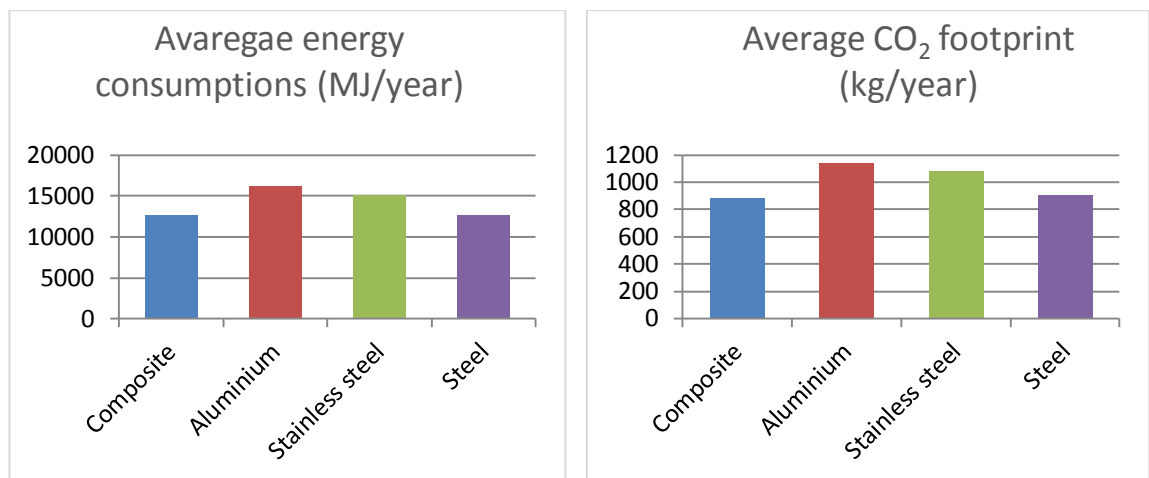

***Figure 26**. Equivalent annual consumption and CO_2 footprint average per a year.*

5.1 CF analysis of transportation assumptions

Two scenario assumptions were evaluated in this study in order to illustrate the difference in using different types of transportation to deliver the products to customers. The first scenario examined in the study is where the transportation of the product was delivered to customers via truck operated by diesel fuel. The distance estimated within the European region is 4500 km. By using equations (3) and (4) taking in consideration the product mass and distance, the energy consumed and CO_2 emissions generated through the transportation are calculated. The results in Figure 27 for the four types of materials show an insignificant effect on the total energy usage during the product life cycle. Furthermore, the CO_2 footprint values in this phase are quite low and contribute to a less than 1 % of the total environmental impacts of the product as shown in Figure 28. Please note that, the values would be different if this phase considers the transportation of raw materials, which is not included in this study. The product weight has a major effect on the energy required as well as the amount of fuel consumed.

In the second scenario, it was assumed that the product is delivered to the customers using a short haul air flight operated by kerosene fuel. This assumption was considered in order to illustrate the difference of transportation and fuel types on the environmental impacts for all the materials. Figure 27 shows the energy used in this phase for four types of materials which ranges between 4.2-4.6% of the total energy used for the life cycle of the product. The highest value is obtained for the stainless steel panel followed by the aluminium panel and finally the lowest was for the composite panel. This can be explained due to the high consumption per kg per km of the kerosene fuel that is about 30% higher than the diesel fuel consumption for the four types of materials.
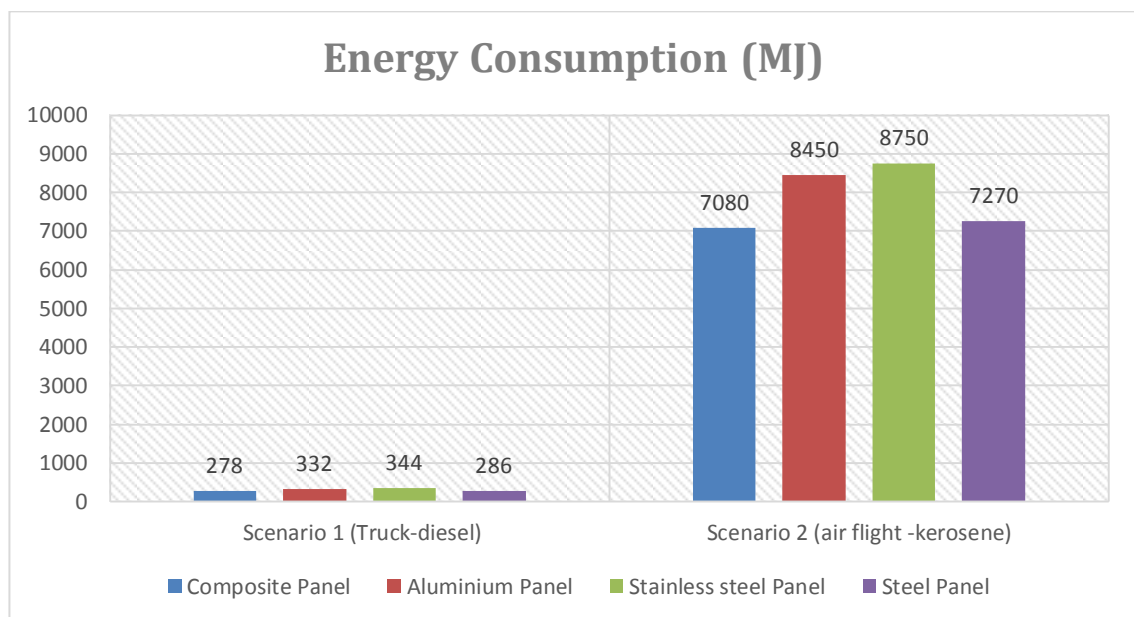
Figure 27. *Transportation phase energy consumption of two different scenarios*

The amount of CO_2 footprint emissions generated in this phase is shown in Figure 28. The values are in a range between 4-4.3 % of the total environmental impact of the product. Both the stainless steel and aluminium panels have the highest values of emissions in comparison to the composite and steel panels. The weight of the conventional materials have significant effect on the fuel consumption and lead to higher values of CF. Whereas, the weight reduction obtained within the composite materials has a lower CF environmental impact.
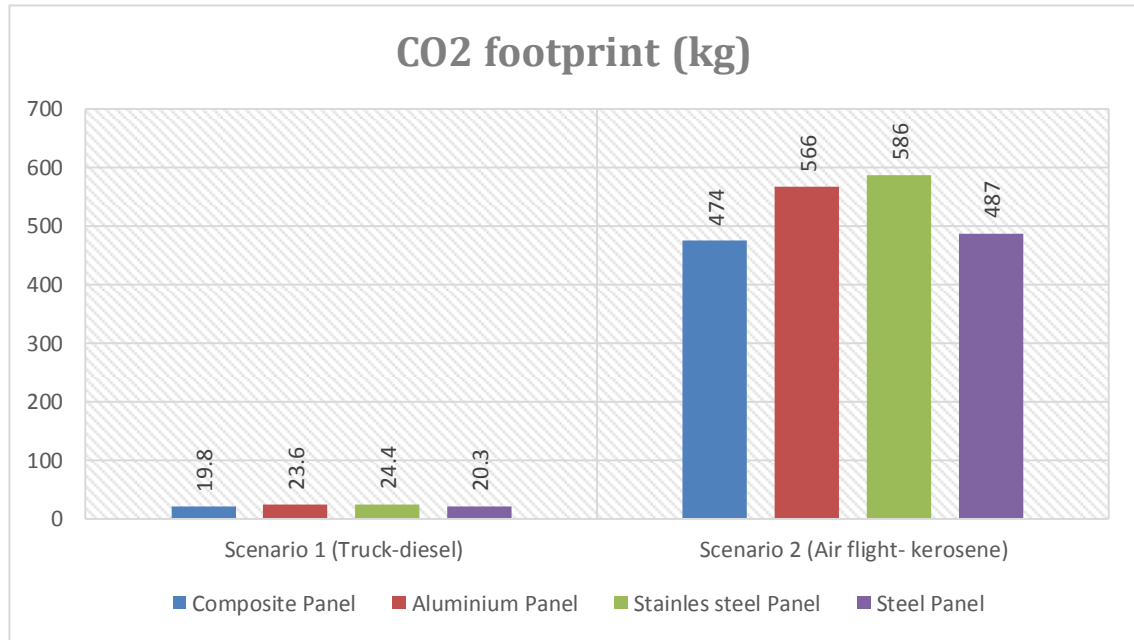
Figure 28. Transportation phase CO₂ footprint of two different scenarios

It can be clearly seen that, the second assumption is not recommended to be implemented in companies due to great environmental impact and energy usage obtained from the use of the kerosene fuel.

5.2   CF analysis of use phase assumptions

Three different mobile use scenarios were examined, this including: a) a diesel family car, b) a gasoline family car and c) an electric family car. The use phase is defined by three parameters: the transport type, the efficiency and the distance travelled over the product's life. In order to determine the contribution of the mobile use for both energy and CO_2, equations (5) and (6) which consider the product usage and distance parameters are employed for the calculations. The results of the energy usage and the CF generated in this phase are displayed in the Figure 29 and Figure 30, respectively.
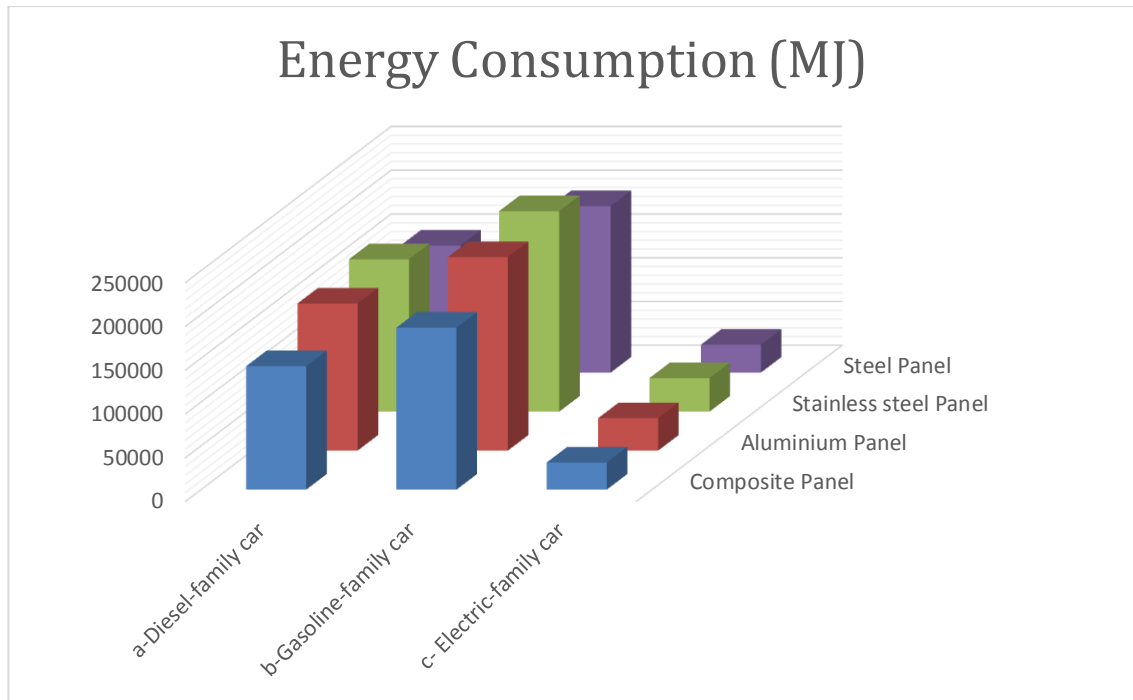
Figure 29. *Use phase energy consumption for the materials with three different case assumptions: a) a diesel-family car, b) a gasoline-family car, c) an electric-family car.*
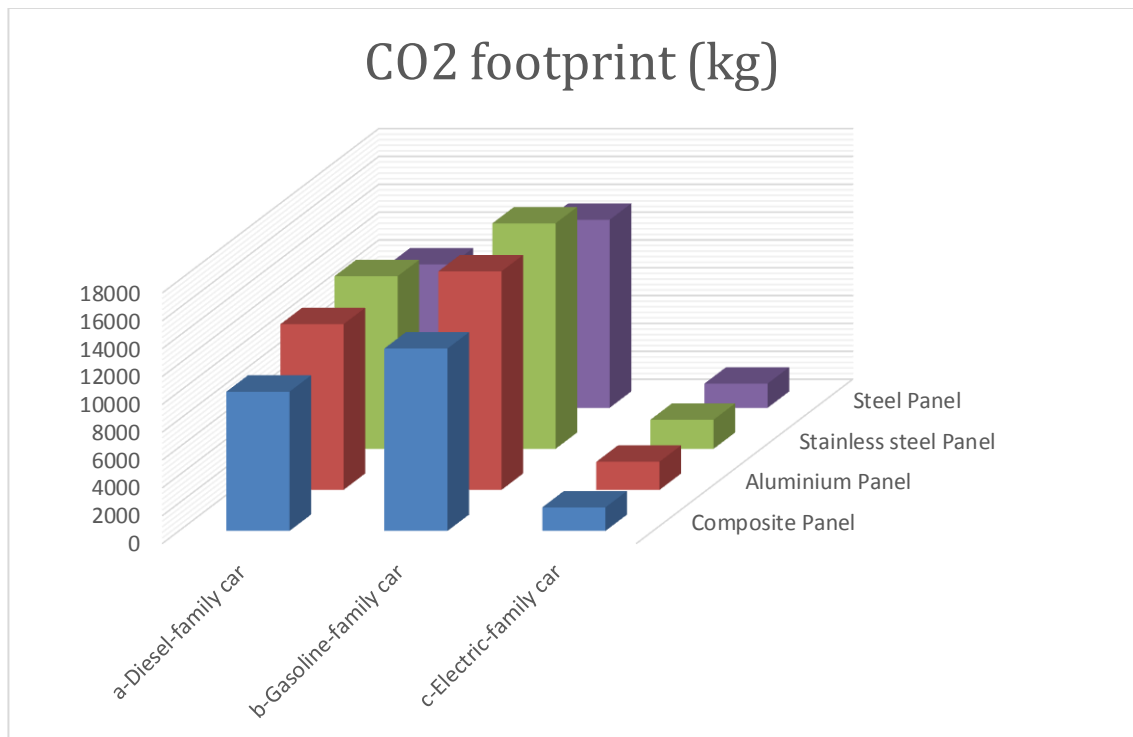
Figure 30. *Use phase CO$_2$ footprint of the materials with three different case assumptions: a) a diesel-family car, b) a gasoline-family car, c) an electric-family car.*

The first scenario which was examined, is the use of the panel as a part of a family car operated by diesel. As previously mentioned, the use phase accounts for a significant amount of total energy consumption and CO$_2$ emissions. In this scenario, the stainless

steel shows the highest values for both the energy use and CF with 96% occupation on the total environmental impact. However, the composite panel indicates lower values of energy use and CF emissions. The weight of the product is a major factor in this phase affecting the calculated values. The stainless steel panel accounts for 64.74 kg and thus, the values are high for the consumption of fuel and higher amount of CO_2 footprint. On the contrary, the low weight of the composite panel resulted in energy saving, fuel efficiency and less amount of CO_2 emissions.

The second scenario is the use of the panel in a family car operated by gasoline. The values of energy consumption and CF emissions for the four types of panels have increased for approximately 25% in comparison with the first scenario (Figure 29). The stainless steel with the highest energy consumptions of $2.29x10^5$ MJ, aluminium panel derives at second with $2.21x10^5$ MJ and steel panel derives at third with $1.9x10^5$ MJ. Whereas, the composite panels demonstrate the least amount of energy used in this phase with $1,86x10^5$ MJ. The main influence in this phase is the amount of gasoline fuel consumed is approximately double than the diesel fuel energy [74]. Moreover, Figure 30 shows the CF values of four panels which they increase comparing to the first scenario. The CF of the stainless steel panel indicates the greatest amount of emissions generated with a value of $1.62x10^4$ kg. The aluminium panel value is $1.57x10^4$ kg and the steel is $1.35x10^4$ kg. However, the composite panel shows the lowest amount of CF emissions emitted by $1.3x10^4$ kg. The weight reduction has a significant contribution in saving energy and fuel consumption.

The third scenario was the family car operated by electricity. This scenario shows a dramatic decrease in the amount of energy usage as well as the CO_2 footprint. The values dropped by approximately 80% of the energy consumed and CO_2 footprint in the gasoline scenario. Therefore, the CF values resulted in a lower amount of emissions in comparison to the first and second scenario. For example the stainless steel panel energy consumption from Figure 29 is $3.83x10^4$ MJ, which is about 83% lower than the values obtained from the second scenario. The CF of this panel is 2090 kg that is about 87% less than the second scenario CF value. Yet, the composite panel still displays the least amount of energy consumption ($3.1x10^4$ MJ) and the lowest amount of emissions in this phase with 1690 kg. Therefore, this scenario has shown a significant improvement in energy saving and reducing the amount of emissions as compared to the first and second scenarios.

5.3 Further work for improvements

The amount of emissions generated in the raw materials extraction and manufacturing of the composite materials can be reduced by using biocomposites. The biocomposite is a type of composite materials derived from natural and renewable sources. Recently, this field of interest is receiving a lot of attention for further research projects due to the high demands for sustainable technologies. Moreover, the environmental potential

benefits of these materials are less CO_2 emissions, lower embodied energy of materials, ease depletion of non-renewable resources and the possibility for biodegradation taking place as an end-of-life option. In addition, the other advantages of the biocomposite materials are their good damping adsorption, weight reduction and health benefits. There are several types of natural fibers used in different applications such as hemp, flax, kenafe and jute [78]. Additionally, a various number of bioresins are introduced to the market such as polyfurfuryl alcohol resins derived from waste sugarcane biomass and polylactic acid (PLA) derived from corn starch [78]. Moreover, different types of recycling methods of composite materials are available as potential end-of-life options such as hydrolysis, chemical recycling, pyrolysis, incineration and regrinding. However, the recycle fraction in current supply is less than 1%, thus most of the materials are sent to landfills [70].

In order to reuse the energy embodied in the composite products, the pyrolysis process decomposes organic materials to reuse them as chemicals and fuel [79]. Furthermore, by using the hydrolysis process it would be possible to recover monomers such as polyamides and polyester [80].

Several studies have been conducted on the recycling of the glass fiber reinforced polyester products over the years. Eventually, three recycling methods were found to provide a promising solution for waste management [81]:

Material recycling: encompasses grounding of glass fiber reinforced polyester products to recyclable materials, which will allow re-using the materials as reinforcements in other composite products or as fillers.

Chemical recycling method: this allows the chemical separation of glass fiber from the polymer matrix (polyester) in order to reuse the fibers and resins again.

Co-processing: the best recycling option for the glass fiber reinforce polyester products which involves regrinding the composite materials. These re-granulates can be used as raw materials for the cement industry as well as using the waste materials as an energy source instead of fossil fuels.

6. CONCLUSION

In this study, Eco-audit tool was used to perform a life cycle analysis and to calculate energy consumption and CO_2 footprint of a pultruded composite side panel and other conventional materials, including aluminium, stainless steel and steel. The environmental impact of pultruded composite side panel and the conventional material were investigated by estimating the energy consumption and CO_2 footprint through the complete life cycles. All of the life cycle phases were taken into account including raw materials extraction, manufacturing, use of the product, transportation and end-of-life phases. This study allowed the comparison among four different materials and highlighted the benefits of using pultruded composite products in automotive applications, especially for coaches.

The results of this analysis have indicated that the aluminium raw materials extraction required a higher embodied energy and a larger amount of CO_2 emissions. The steel panel energy usage during the manufacturing phase has a significant negative environmental impact due to the applied finishing processes. The energy consumption and the CO_2 emissions of the use phase dominate the life cycle of automobiles. Due to the lighter weight of the pultruded products, this has shown clear advantages over the entire life cycle concerning weight reduction, saving energy by lowering the fuel consumption and reducing impacts from vehicles. Even though, the composite materials are not recyclable, the benefits obtained from the lightweight materials compensate any potential paybacks from recycling.

Two scenario cases of transportation assumptions were analyzed during the study. The results show the advantages of using the composite materials in transportation by a diesel truck which tends to have lower environmental impacts. Furthermore, three scenario cases were assumed in the use phase for different types of fuel. High amount of energy consumed in the gasoline-family car type in comparison with the use of an electrical car, which results in approximately 80% reduction of CO_2 emissions. The weight reduction of the composite materials show advantages through these assumptions in both the transportation phase and use phase.

Finally, the current recommendations for the automotive manufacturers are to reduce the amount of emissions at the use phase and to increase the recycling rate of the composite materials at the end-of-life phase. Nevertheless, there is an essential need to implement the biocomposite materials towards more environmentally sustainable technologies.

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APPENDIX: TERMS AND DEFINITIONS

Business-to-business	Provision of inputs, including products, to another party that is not the end user [19].
Business-to-consumer	Provision of inputs, including products, to another party that is not the end user [19].
Carbon dioxide equivalent (CO$_2$e)	Unit for comparing the radiative forcing of a greenhouse gas to carbon dioxide [19].
Carbon footprint	Is a term used to describe the amount of greenhouse gas (GHG) emissions caused by a particular activity or entity, and thus a way for organizations and individuals to assess their contribution to climate change [19].
Carbon footprint of product (CFP) communication programme	Programme for the development and use of CFP communication based on a set of operating rules [10].
Carbon footprint of product CFP label	Mark on a product identifying its CFP within a particular product category according to the requirements of a CFP communication programme [10].
CES Selector	Is a PC application that enables materials experts and product development teams to find, explore, and apply materials property data [62].
Climate Change	Refers to any significant change in the measures of climate lasting for an extended period of time. In other words, climate change includes major changes in temperature, precipitation, or wind patterns, among others, that occur over several decades or longer [85].

Cradle-to-gate	A product's life cycle stages from the extraction or acquisition of raw materials to the point at which the product leaves the organization undertaking the assessment [19].
Cradle-to-grave	A Product's life cycle from raw material acquisition through production, use, end-of life treatment, recycling and final disposal [22].
Eco Audit	Is an add on tool in CES Selector which allows to quickly assesses a product design to identify the major contributors to environmental impact, helping to make effective design choices [62].
Environmental impact	Consequences of pollution
Functional unit	Quantified performance of a product system for use as a reference unit [21].
Global warming potential (GWP)	Factor describing the radiative forcing impact of one mass-based unit of a given greenhouse gas relative to an equivalent unit of CO_2 over a given period of time [19].
Greenhouse Gases	Gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere and clouds [19].
Impact category	Class representing environmental issues of concern to which life cycle inventory analysis results may be presented [10].

Kyoto Protocol	A protocol to the United Nations Framework Convention on Climate Change (UNFCCC). Once entered into force it will require countries listed in its Annex B (developed nations) to meet reduction targets of GHG emissions relative to their 1990 levels during the period of 2008-12 [28].
Land use change	Change in the purpose for which land is used by humans (e.g. between crop land, grass land, forest land, wetland, industrial land) [19].
Life Cycle	Consecutive and interlinked stages of a product system, from raw material acquisition or generation of natural resources to end of life, inclusive of any recycling or recovery activity [21].
Life Cycle Assessment (LCA)	Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle [21].
Primary activity data	Quantitative measurement of activity from product's life cycle that, when multiplied by the appropriate emission factor, determines the GHG emissions arising from a process.[19].
Primary data	Quantified value of a unit process or an activity obtained from a direct measurement or a calculation based on direct measurements at its original source [10].
Product category rules (PCR)	Set of specific rules, requirements and guidelines for developing Type III environmental declarations for one or more product categories [47].

Pultrusion	Is a continuous process for manufacture of composite materials with constant cross-section [84].
Secondary data	Data obtained from sources other than direct measurement of the emissions from processes included in the life cycle of the product [19].
Secondary data	Data obtained from sources other than a direct measurement or a calculation based on direct measurements at the original source [10]
Sensitivity analysis	Systematic procedures for estimating the effects of the choices made regarding methods and data on the outcome of a CFP study [10].
System boundary	Set of criteria specifying which unit processes are part of a product system [19].
Unit process	Smallest element considered in life cycle inventory analysis for which input and output data are quantified [10].
Use phase	That part of the life cycle of a product that occurs between the transfer of the product to the consumer and the point of transfer to recycling and waste disposal [19].