

Life Cycle Evaluation of Manufacturing and Mechanical Properties for Novel Natural Fibre Composites

By

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Abstract

Life Cycle Assessment (LCA) is a method for evaluating the environmental impacts associated with all stages of a product's life-cycle (production, use and disposal) by identifying, e.g., energy consumption and CO₂ emissions. This work has been aiming for a life cycle assessment for the manufacturing of natural flax fibre roving reinforced composites. The research focused on the processing gate-to-gate (GtG) system boundaries through tests and analysis of the energy consumptions and carbon foot-prints based on real primary data. The working data was obtained from specialists and composite manufacturers using a monitoring computer, ecoinvent software, connected to the machine. Then, SimaPro 8 for LCA was used to produce the process tree and to determine the environmental impact of the production through auto indication. The overall LCA of the natural fibre composites production is reflected by using a limited number of stages on targeted energy consumptions within the "factory-door-in to factory-door-out", which have been determined and assessed in the designed in-situ or in-line operation processes.

The composite material is comprised of a flax roving, polylactic acid (PLA) and maleic anhydride polypropylene (MAPP). This matrix is commingled in the process for new composite material in the form of a flax/PLA and flax/MAPP tape according to the technical requirements by industry. The quality of the composite tape is dependent on the temperature and roving speed in manufacturing. The processing condition was optimised and it was found that the best processing rate was at a temperature of 170 °C and speed of 4.0 m/min. The results showed that flax/PLA and flax/MAPP mixed well as a matrix material for natural fibre composite. In contrast, the normal tri-axial glass fibre production is optimised with a speed of 1m/min using a standard roving glass fibre laminating machine. The composite flax/PLA tape, however, is about four times faster compared with the normal tri-axial manufacturing. The life cycle gate-to-gate results of the process showed that the energy consumption, to produce 1.0 kg of flax/PLA tape or flax/MAPP tape was 4.4 MJ, and the CO₂ emissions were estimated at 0.63 kg. The energy consumption to produce a similar amount of glass fabrics for composites is about 23.8 MJ with CO₂ emissions estimated to be at the level of 3.45 kg. Therefore, the process to manufacture flax/PLA tape can be produced considerably quicker than that of woven fibreglass fabrics for glass fibre composites.

As an important part of the composites processes, moulding composites flax/PLA or flax/MAPP tape were primarily accounted and analysed. The suggested standard procedures, to perform the processing setup, were used throughout the work to avoid the

dry region or non-impregnated fibres during the moulding process. The energy consumption and environmental impacts, of the compression moulding process for the composite flax/PLA tape, were evaluated and compared to the composite glass/PP. The results show that the electricity used for the compression moulding process varies between 17 MJ to 19 MJ for the composite flax/PLA tape and glass/PP. Still, the environmental impact of the composite glass/PP is largely superior to that of the composite flax/PLA tape.

More detailed processing comparisons of composite flax/PLA were carried out regarding energy consumption and CO₂ emissions, in a production of a car component, by using an eight layer-flax prepreg tape through a conventional hot press-moulding. The moulding data displayed showed that to produce a 250 mm x 250 mm sheet, estimated energy consumption was 17.1 MJ, and the CO₂ emission was 2.6 kg. Meanwhile, the ultimate tensile strength achieved was between 57 MPa to 105 MPa and the flexural strength was between 10 MPa to 80 MPa. Production results portrayed that a tape composition with 60% volume fraction Flax and 40% volume fraction PLA resulted in better tensile properties than other volumetric ratios. The outcomes may support alternative options for some material applications and selections for the automotive industry such as boot trim, door insert, parcel shelf and truck interior.

An effort was made to optimise the mechanical properties of composites flax/PLA and flax/MAPP, mainly, through calculations of the thickness using flexural modulus formula three-point bend. Based on the experiment results of the mechanical properties observed, the thickness of the natural fibre composites flax/PLA and flax/MAPP tape is 2.1 mm lower than for the composite, whereas glass unit directional (glass UD) fabric is 3.5 mm. This is primarily when focusing on the specific composite properties as a result of the low density of natural fibre. The flexural modulus of the composite tape is significantly lower than that of their counterpart composite materials glass/PP or glass UD fabric. The flexural modulus formula of natural fibre composite material and glass/PP or glass UD fabric were combined to find the require thickness need to add to the composite flax/PLA and flax/MAPP tape. The outcomes show that natural materials flax/PLA and flax/MAPP tape have breadth increased to 5 mm and to 8 mm respectively to be equivalent to the stiffness of composite glass unit directional fabric. Therefore, enhancing the thickness improved the mechanical properties, while other dimensions (length and width) stay the same, whilst increasing the energy consumption for the compression moulding.

A life cycle gate-to-gate was used to compare material transformation, fibre into fabric and fibre into the composite tape, by a current production method using a tape machine and

triaxial machine. This was followed by prepreg and compression moulding, into the component that can be used for automotive applications. The results of the life cycle process indicated that the negative effect on human health, of natural fibre composite tape, is lower than the synthetic fibre and is, therefore, an ecologically friendly alternative. However, because of limitations of the life cycle method, the results are only an interpretation and not the absolute truth, as some factors like the effect of heat loss and machine wear and tear were not included in the analysis. The evaluation of the manufacturing process shows different environmental effects. Therefore, the outcomes may support alternative options for some material productions and less environmental impact.

Keywords: polylactic acid (PLA), maleic anhydride polypropylene (MAPP), flax, carbon dioxide emissions (CO₂e), gate-to-gate (GtG), life cycle assessment (LCA) polypropylene (PP).

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- Training Life Cycle Assessment (LCA)

Introduction and Intermediate LCA Workshop

Brief summary of the thesis

The thesis introduces a brief history of life cycle assessment (LCA) uses in the past decade. Moreover, material transformation such as natural fibre flax, hemp, and PLA is made into fabrics that can be used in the automotive industry. This Chapter also presents the aims and objectives of the research as well as the general approach with an overview of the research plan.

The literature survey presents the development and progress of natural fibre for engineering applications. It has shown a brief history of natural fibres such as flax and PLA compared to some synthetic fibres. Different software is presented and discussed to evaluate advances in the development of natural fibres through the manufacturing process. Simapro LCA is an industry-standard software developed to assess advanced manufacturing through material production until the end of life. Moreover, it is discussed how legislation on the environment influences the quality of the product and process. The manufacturing and material processing was present in this chapter to show the composite material process and how it was produced, while presenting the embodied energy and carbon storage yield for each operation of the development of composite materials. The method used to measure the mechanical properties were present to evaluate the mechanical properties of the composite material products, for a better improvement based on the manufacturing method and energy saving.

The materials and methodology present the resources used to develop the life cycle assessment GtG. It also refers to the process, environment, impact of LCA GtG and software used to evaluate and analyse the process, energy consumption calculations, and conversion factors. The system boundary showed the input and output of the manufacturing process and examined, the functional unit attributes to the primary data. This shows us how to interpret data on Simapro 8 to produce a simulation of the manufacturing process and the environmental impact. The simulation demonstrates how to explore different options to improve the results.

The results are formed in two parts, production of composites flax tape and triaxial glass fibre fabric. The first part is the material production phase for life cycle assessment, which describes the process used to produce flax/PLA and flax/MAPP fabric tapes and the moulding process, which links to energy consumption and carbon dioxide emission. This part describes the manufacturing process of triaxial glass fibre, which covers the moulding process and the manufacturing process linked to energy consumption at each step of the production. The moulding process was investigated to produce the part of the composite materials and analysis. The test results of the mechanical properties of new materials,

such as tensile strength and flexural modulus were used to select the best combination of flax/PLA or flax/MAPP.

This Chapter shows the simulation results using Simapro 8 by producing the manufacturing process tree and the environmental impact of the process. The work done on LCA, divided into different sections, the natural fibre, glass fibre production and the compression moulding used to make all those processes. There is a brief explanation of electricity usage.

This Chapter evaluates and analyses the results obtained in Chapter 4 and introduces a new methodology, by using data from up-to-date literature to compare the results and process through Life Cycle Assessment using SimaPro software. Based on the results obtained in Chapter 4 and the data presented in Chapter 2, the methodology of the approach was developed and implemented. The energy consumption to produce natural fibre and synthetic material with equivalent stiffness properties based on the thickness using a compression moulding process, is calculated.

The conclusion and future work itemises the main highlights and findings of the project, with final remarks on the project. Moreover, future work on the project is suggested.

Flow chart overview of the thesis

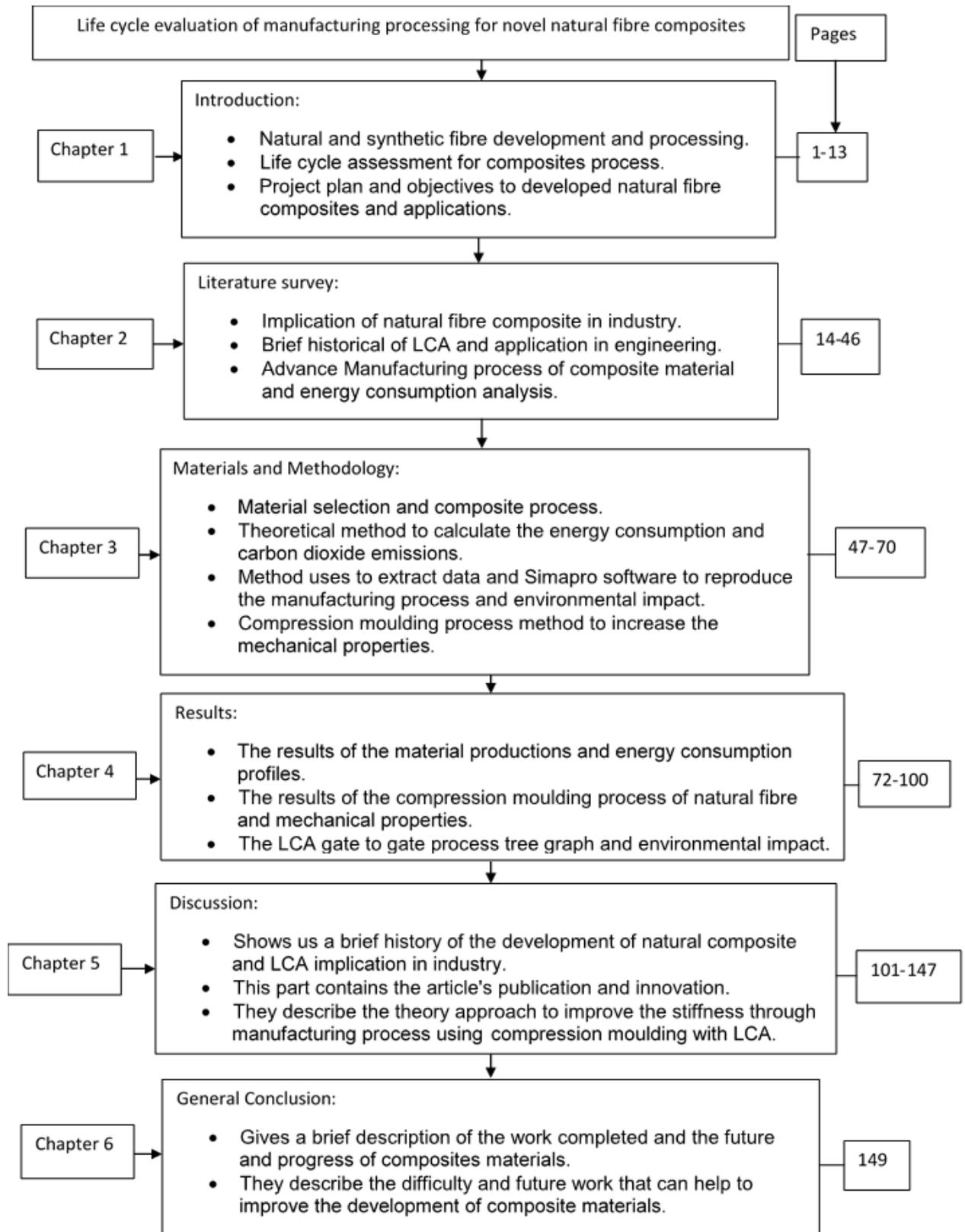


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Glossary

BS	British Standard
CF	Carbon Fibre
CFRP	Carbon Fibre Reinforced Plastics
CO ₂ e	Carbon Dioxide Emissions
e	emissions
E	Energy
EI	Environment Impact
Fl	Flax
GF	Glass Fibre
GPa	Giga Pascal
GtG	Gate-to-Gate
GWP	Global Warming Potential
ISO	International Standard Organisation
KWh	kilowatt hour
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis
LCIA	Life-cycle Impact Assessment
MAPP	Maleic Anhydride Polypropylene sliver
MJ	Mega Joule
NFC	Natural fibre composite
OM	Optical Microscopy
P	Polythene
PLA	Polylactic Acid
PP	Polypropylene
PP/SGF	polypropylene/short glass fibres
PP-g-MA	Maleic anhydride grafted polypropylene
SEBS-g-MA	Maleic anhydride grafted styrene-ethylene-butylene-styrene
SFMC	short fibre moulding composite
t	Time
TGFF	Triaxial glass fibre fabric
TPS	Thermoplastic
SEM	Scanning Electron Microscope
UK	United Kingdom

UPE	Unsaturated Polyester (UPE)
V	Volume of the composite
VE	Vinyl ester
v_f	Fibre volume fraction
V_f	Volume of fibres
v_m	Matrix volume fraction
V_m	Volume of matrix
W	Weight of the composite
w_f	Fibre weight fraction
W_f	Weight of fibres
w_m	Matrix weight fraction
W_t	Wettability
W_t	Wettability
WWT	Waste Water Treatment
ρ	density
ρ_f	density of fibres
ρ_m	density of the matrix

Chapter 1: Introduction

This section introduces the interest of the natural fibre and process for composite application for industry. This presents a brief history of life cycle assessment (LCA) used in the past decade. Moreover, the material transformation such as natural fibre flax, hemp, and PLA in-to fabrics, that can be used in the automotive industry, is explained. This chapter also shows the aims and objectives of the research as well as the general approach, with an overview of the research plan.

1.1 Material development

The use of composite materials dates from centuries ago with people using natural fibres. Government environmental policies have been implemented to force industries such as automotive, packaging and construction, to search for environmentally friendly or biodegradable materials to substitute the traditional non-biodegradable composites. Therefore, natural fibres as reinforcement in polymer composites have generated more interest to establish best practice in each stage of the transformation, due to the environmental legislation and improvements on natural fibre performance and processabilities [1-3]. The composite productions and standard polymeric systems can be divided into two systems: thermosets and thermoplastics. The thermosets cover mainly epoxy resin, polyester resin, phenolic resin systems, and polyurethane resin systems. Some prevalent thermoplastic systems are also used in the current automotive industry, such as polyethylene (PE) and polypropylene (PP). Polymer fibres are traditionally classified into natural and synthetic. The natural fibre is generated in natural conditions like flax, cotton, hemp. Synthetic fibre such as glass, carbon is a subset of human-made fibre, which are based on synthetic chemicals rather than arising from natural materials by a purely physical process [4]. Natural fibre composites are emerging as realistic alternatives to synthetic composite material in many applications. Therefore, it is essential to investigate the environmental impact of some natural fibre compared to some synthetic composite materials according to Ren, G.P.(International conference on composite material) [2]. Research has shown that natural fibres can be combined with matrix resins to produce composites that exhibit mechanical and physical properties similar to those made from fossil-based polymers reinforced [5]. Therefore, the relative sustainability of biocomposites should be observed at all stages of development through Life Cycle Assessment (LCA) to estimate energy consumption and to improve the process. The global requirement for reduction of carbon dioxide emission and increasing vehicle fuel economy is an important aspect of technology development of natural composite materials in the transportation Industry [6]. The primary goal of this work is to address two

significant challenges in the automotive industry: weight reduction, and incorporation of renewable materials in to the composite structures that this technology enables [7]. The relationships between natural fibre properties and resin matrix properties are more complex than those in glass fibre reinforced composites [8]. After decades of high-tech developments of artificial textures like glass, carbon and aramid, it is remarkable that there is renewed interest in natural fibres as potential reinforcements for composites instead of human-made fibres. The UK government publication “Securing the Future: Delivering UK Sustainable Development Strategy” emphasised sustainability in both industries and agriculture with a revival of interest in materials from sustainable sources [9].

As opposed to common metal materials, fibres have anisotropic properties. High modulus and strength in one direction are accompanied by only limited strength in the lateral dimension. However, in many applications, just one direction is, in fact hardly strained. Moreover, combining different fibres, such as Flax, Polylactide acid (PLA) , and MAPP (Maleic Anhydride Polypropylene) and cores with an appropriate matrix allows the design of specific material properties [10]. The increased interest in natural fibre-reinforced composites is due to the high performance in mechanical properties, significant processing advantages and excellent chemical resistance [11]. The mechanical properties of natural composite materials are determined by their structure, which includes the arrangement and the bond between fibres and matrix. The natural fibres properties depend on its' molecules structure, which is affected by growing conditions, location and the fibre processing techniques. However, natural fibres have been reported to have excellent tensile strength and modulus, high durability, low bulk density, good moldability and recyclability [12].

Interfaces play a significant role in the physical and mechanical properties of composites [13]. The improvement of natural fibre-matrix adhesion should be commonly modified to better match fibre surface properties. Conversely, simple chemical treatments such as plasma infusion can be applied to the fibre with the aim to change surface tension and polarity through modification of fibre surface and improve the strength of the composite material. Nevertheless, plasma infusion process has to test deeper to estimate the level of infusion on the material.

Depending on their origin, natural fibres are grouped into seed, bast leaf and fruit categories. Bast (stem) fibres from plants such as flax, hemp, kenaf, jute, and ramie are more likely to be adopted as reinforcement in composites. These bast fibres are advantageous over the other cellulose-based fibres (seed fibre, leaf fibre or fruit fibre) due

to high modulus, tensile strength and low specific gravity, for example, stiffness and strength to weight ratios [14]. Flax is chosen for this research because of the suitable availability and generally overall mechanical and physical properties when compared to other materials Appendix A, section 1.A and 2.A.

Fibres like flax/linseed and hemp are currently grown commercially in UK/Europe and used in natural fibre composites for a broad range of automotive applications such as the interior panels of passenger cars and truck cabins, door panels and cabin linings as substitutes for glass fibre composites [15].

For flax crop growing, the utilisation of fertilisers may result in nitrogen runoff causing environmental impacts such as acidification, aquatic toxicity, human toxicity and eutrophication. Primary sources of greenhouse gases which contribute to global warming and hence perhaps to climate change are from energy used to power farming equipment and to produce and apply fertilisers and pesticides in flax fibre production, and during the transformation processes [16].

Glass is the most common fibre system used in polymer matrix composites [16]. A variety of different chemical compositions are commercially available [17]. Common glass fibres are silica based and contain a host of other oxides of calcium, boron, sodium, aluminium, and iron. The structure of glasses in their solid state, consist of rigid network of silica or silicates [17]. The network structure is responsible for their superior rigidity and strength. The variation of glass properties can be achieved by modifying the structure of silica with various additives. Among all the glass fibres used in composites, E-glass is the type most widely used. The treatment of the glass fibres provides a suitable surface condition compatible with that of resin matrix, so that good adhesion can be achieved. Unsatisfactory bonding between the fibres and matrix can cause interfacial failure, and stress will not be transferred effectively at the weakened spot [17].

Glass fibre production contributes to global warming due to the energy used in the manufacture. The associated emissions (volatile organic compounds) lead to ozone depletion, photochemical oxidants creation and human toxicity [16]. Publicly available information on energy and material inputs of glass fibre production are scarce. In Zogg [18] an energy equivalent of 286 MJ/kg is reported, more than 10 times the energy required for the production of one kg of steel. Toray Industries Inc. estimated total energy consumption roughly to be 280 - 340 MJ/kg [19].

Polypropylene is similar chemically to high-density polythene. It is made from polypropylene gas and consists of carbon and hydrogen atom only. Polypropylene is an extremely versatile resin and is available in many grades and also as a copolymer (ethylene / propylene). It has the lowest density of all thermoplastics (in the order of 900 kg/m³) and this combined with strength, stiffness and excellent fatigue and chemical resistance makes it attractive in many situations [20]. Polypropylene is low in cost, which is due to a relatively simple synthesis from the low cost petrochemical: propylene. To be useful in a wider range of applications, polypropylene is often copolymerised with others materials like polythene, yielding a material with the temperature resistance, stiffness and strength of polypropylene, but better impact resistance contributed by the flexible linkages of the material. Polypropylene is used widely in film, fibre, sheet, and moulded applications. Most of the film is used in packaging. The fibre is used in carpeting, upholstery and apparel due to its wear and chemical resistance [21]. Common moulded applications include bottle, pipes, containers, and tanks. Due to its low cost, polypropylene is used in toys, and disposable houseware [21].

Fabiola Vilaseca and Alex Valadez-Gonzalez [22] evaluating through Bio composites abaca strands were used as reinforcement of polypropylene matrix and their tensile mechanical properties were studied. It was found relevant increments on the tensile properties of the abaca strand-PP composites despite the lack of good adhesion at fibre–matrix interface [22]. Afterwards, it was stated the influence of using maleate anhydride polypropylene (MAPP) as compatibilizer to promote the interaction between abaca strands and polypropylene. The intrinsic mechanical properties of the reinforcement were evaluated and used for modelling both the tensile strength and elastic modulus of the composites. For these cases, the compatibility factor for the ultimate tensile strength was deduced from the modified rule of mixtures [22]. Additionally, the experimental fibre orientation coefficient was measured, allowing determining the interfacial shear strengths of the composites and the critical fibre length of the abaca strand reinforcement. The mechanical improvement was compared to that obtained for fiberglass-reinforced PP composites and evaluated under an economical and technical point of view [22].

1.2 Life cycle assessment on composite materials

Life Cycle Assessment (LCA) is an environmental assessment method which, according to the international standard Environmental Management. Principles and frameworks, ISO 14040:2006(E), “considers the entire life cycle of a product from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end-of-life treatment and final disposal” [23]. It can be used to assess whether the claimed environmental benefits of the materials can be justified. An LCA study has four phases:

- The goal and scope definition – aims and objectives of the study
- Life Cycle Inventory Analysis (LCI) – compilation and quantification of inputs and outputs for a product through its life-cycle.
- Life Cycle Impact Assessment (LCIA) - understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system throughout the life cycle of the product.
- Life Cycle Interpretation – the findings of the LCI or LCIA or both are evaluated about the defined goal and scope to reach conclusions and recommendations.

Jonathon Porritt in *Capitalism As If The World Matters* in 2005 [24] has said,

"One of the most popular tools used by companies to achieve these efficiency gains is life-cycle analysis, assessing the impact of a product from manufacture through to final disposal, reuse or recycling. It sounds simple, but I suspect few people understand the complexity of the kind of analysis that has to be done to work out how best to make those gains".

While the concept of the LCA is simple, the analysis is quite complex in reality, primarily due to the difficulty in establishing the exact system boundaries, obtaining accurate data and interpreting the results correctly [25].

A study was conducted by Vink [26] on life cycle assessment of end of life options for two biodegradable material PLA (Polylactic acid) and TPS (Thermoplastic). They developed specific inventory models of PLA and TPS end-of-life treatments for industrial composting, anaerobic digestion as well as for landfilling and incinerations (MSWI and DFS). They find out that Greenhouse gas emissions are differentiated between the emissions in the first 100 years that are considered for the 100-years horizon impacts, and the subsequent emissions that are also taken into account in the long term global warming impacts. Therefore, the estimation and results was obtained through Secondary data software from the ecoinvent 2.2 database [27]. Since the aim of this paper is to study whether well-developed end-of-life options are environmentally desirable, we assume that PLA and

TPS would reach the threshold justifying a separate stream as is currently the case for polyethylene terephthalate (PET), b) that the required infrastructure is in place for all end-of-life options studied (including the “integrated framework” described by Ren) [28]; and c) that the studied materials are accepted by all treatment options [27].

A study was carried out by Maureen E. and James B. [29] to determine Gate-to-Gate (GtG) life cycle inventory of glued-laminated Timbers (glulam) production in two regions of the United States. The scope of the study was to evaluate through LCI the energy use for the manufacture of glulam timber for two major wood product-producing regions in the United States. The Pacific Northwest (PNW) representing Oregon and Washington, and the Southeast (SE) representing Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, and Texas [29]. This report documents the life-cycle inventory (LCI) of glulam beam manufacture based on softwood resources from the two regions. While primary data were collected through surveys, secondary data were obtained from available databases [30-33]. The LCI presented is focused on two main environmental assessments:

- 1) Energy requirements;
- 2) Emissions to the environment for the production of glulam by the CORRIM Research Guidelines and the International Organization for Standardization (ISO) protocol for performing life-cycle assessments (ISO 1997, 1998) [34, 35];

Before this report work, a few have attempted to assess the environmental impact of an assortment of wood products [36]. Richter’s [37] assessment of glulam timbers on manufacturing process stages, but we are not sure of the quality of data because we do not know which software have been using to recorded the primary data .All conversion units for fuels and forest products followed published factors unique to the industry in each region [38]. An international LCA software package (SimaPro5) designed for analysing the environmental impact of products was used to develop the glulam life-cycle inventory (LCI) [39]. This LCA software also contains a U.S. database for some materials, including paper products, fuels, and chemicals [39]. Process energy for electric power required for glulam production for both cumulative (includes lumber and resin production).Moreover, on-site (gate-to-gate) models was 525 MJ/m³ and 249 MJ/m³ of glulam in the PNW region and 556 MJ/m³ and 290 MJ/m³ for cumulative and on-site (gate-to-gate) in the SE region [40]. When comparing total energy for electric power differences between cumulative (lumber, resin, and glulam production) and on-site (glulam production) models, the burdens associated with lumber and resin production increased energy demand for electricity by 116% in the PNW and 92% in the SE region [40]. Richter’s [41] assessment of glulam timbers included information on energy and air emissions for harvesting,

manufacturing, and transportation stages, but excluded the type of energy and their subsequent air and water emissions and solid waste. Moreover, the manufacturing process was established without any specific energy consumption at each step of the process. More information about each step of the production can be associated with electricity use and carbon dioxide emissions.

A comparison manufacturing process using LCA was carried out by Cargill INC [42] to produce PLA made with 100% renewable resources like corn, sugar beets or rice. He compares two major routes through LCA cradle to gate for the production of PLA 1 and Biomass wind energy PLA (PLA B(WP)) [43]. Therefore, the first process of production of PLA 1 was by direct condensation polymerization of lactic acid with a total energy required 54.1 MJ/kg PLA [44]. Moreover, the second route by ring-opening polymerization through the lactide intermediate with biomass feedstock and wind energy input (PLA B (WP)) with a total power consumption 29.2 MJ/kg PLA [44]. He concludes that data for PLA1 and PLA B (WP) represent engineering estimated and there is a good reason to expect improvement in the actual performance versus the estimates [45]. LCA give us crucial information on the manufacturing process of both method through the system boundary, and the production of PLA1 required more energy that PLA B (WP) with a reduction of 19.6 MJ/Kg PLA [42].

A study was carried out by Joshi [46] to determine the most environmentally friendly reinforcement for composites between natural fibres and glass fibres. They were assessed through a similar LCA technique for a glass fibre reinforced composite component and natural fibre reinforced composite component. It was suggested that the non-renewable energy required to produce a flax fibre mat is 9550 MJ/tonne and China reed fibre mat is 3640 MJ/tonne considering the seed production, fertiliser, transport, cultivation, fibre extraction and mat production. The German study in 1999 by Diener, the energy used to produce a glass fibre mat is 54700 MJ/tonne accounting for raw materials, mixture, transport, melting, spinning and mat production [47]. The scope of each of above assessments is limited by ignoring the use of agriculture machinery, agrochemicals and stages of fibre processing.

A comparative study by Van Dam [48] on environmental implications of manufacture of polypropylene (PP), high-density polyethene (HDPE) and polyurethane (PU) fibres about natural fibre based products. Moreover, concluded that jute fibre production requires less than 10% of the energy used for PP fibres (energy requirement is around 90000 MJ/tonne). When the use of fertiliser was included in the calculations, the energy

requirement for fibre production increased to about 15% of that for PP fibres. However, the data are for jute fibres produced without powered mechanical assistance, and environmental impacts other than energy use were not considered in the above study.

An environmental comparison of China Reed fibre (which are obtained by grinding and sieving of the stem), as a substitute for glass fibre in plastic transport pallets. Therefore, Corbière-Nicollier [49] found that cultivation of the reed had a dominant role in the factors for terrestrial ecotoxicity, human toxicity (when crop rotation has China Reed followed by edible food). Moreover, eutrophication due to (a) heavy metal emissions to soil from diesel usage and (b) phosphate emissions (from manure and fertiliser) to water. This process is based on LCA Cradle to Cradle, and the percentage of toxicity on soil has to be estimated using LCA standard.

The environmental impact of metal production was assessed by Norgate and Jahanshahi [50] using LCA cradle to gate methodology to compare the process, energy and carbon dioxide for the production of some metal. Therefore, the results of the process was obtained by comparing different method for the production of some metal such as Nickel with electricity at 114 MJ/kg [50] and Aluminium at electricity 211 MJ/kg [51]. It was assumed that electricity was generated from black coal in all cases [51-56]. Therefore it could be argued that unit mass of pure metal is not the most appropriate functional unit for the later metals. However, even for these metals, such information is useful, even if not for comparative purposes. For this reason, a functional unit of 1 kg of refined metal was used in the LCAs [57]. For those processes where more than one metallic product is produced, the environmental impacts were allocated to the metallic products on an equal weighting mass basis. No allocation of environmental impacts was made to any acid produced. In fact, there are many factors or parameters associated with a particular metal production process that influence the “cradle-to-gate” environmental impacts of the process. These include, electricity energy source, fuel types, and material transport as well as process technology.

Pickering [58] investigated the optimization of New Zealand grown hemp fibre reinforced PP composites. The optimum growing period was found to be 114 days, producing fibres with an average tensile strength of 857 MPa and a Young's modulus of 58 GPa. The strongest composite consisted of PP with 40 wt% fibre and 3 wt% MAPP, and had a tensile strength of 47.2 MPa, and a Young's modulus of 4.88 GPa.

Xiaoya Chen and Qipeng Guo [59] studied the mechanical properties of Bamboo fibre-reinforced polypropylene composites. They used a new type of bamboo fibre-reinforced polypropylene (PP) composite to prepare the sample and its mechanical properties were tested. To enhance the adhesion between the bamboo fibre and the polypropylene matrix, maleic anhydride-grafted polypropylene (MAPP) was prepared and used as a compatibility for the composite. The maleic anhydride content of the MAPP was 0.5 wt. %. It was found that with 24 wt. % of such MAPP being used in the composite formulation, the mechanical properties of the composite such as the tensile modulus, the tensile strength, and the impact strength all increased significantly. The new composite has a tensile strength of 32–36 MPa and a tensile modulus of 5–6 GPa. Compared to the commercially available wood pulp board, the new material is lighter, water-resistant, cheaper, and more importantly, has a tensile strength that is more than three times higher than that of the commercial product.

Thwe and Liao [60] examined the effect of coupling agent (maleic anhydride polypropylene) on the tensile and flexural properties of BF-reinforced PP and bamboo-glass fibre-reinforced PP hybrid composites. It was shown that the presence of coupling agent and hybridization with natural fibre is a viable approach for enhancing the mechanical properties and durability of natural fibre composites.

The cited literature on LCA studies rarely considers the full four environmental impact classification factors (EICF) as outlined in ISO/TR 14047/2003 [61] and are mainly referenced to a specific end product. Therefore a comparative quantitative LCA considering the environmental impact factors for flax fibre would help to identify whether the substitution of glass fibres with natural fibres is truly environmentally beneficial. In particular, while governments and the media are currently preoccupied with global warming/climate change. Therefore, there is increasing concern expressed by pressure groups in respect of the availability of potable water, the use of land for industrial products (fibre, feedstock and fuel) rather than for food and loss of biodiversity arising from acidification, eutrophication and toxicity [16].

The scope of this LCA will focus on gate-to-gate (from composites factory door in to door out) but not limited and the functional unit of the analysis is regarded as kilogramme or tonne of fibre ready for reinforcement in polymer matrix composites. They will be a different level of the production and transformation of flax fibre on this study until end product. The production and transformation of flax fibre considered in this study are:

- Flax sliver, PLA and MAPP into flax tape;
- Infusion of flax using plasma machine to improve mechanical property;
- Flat tape transform into composite materials and testing;
- Flax tape(Infusion plasma) transform into component;

In the context of LCI, inputs (such as energy and materials) and outputs (such as emissions) are quantified at each production stage of flax fibre. The environmental issues analysed in LCIA is: - Global Warming Potential (GWP);

The reasons for the preference of natural fibres over synthetic fibres in composites (e.g. glass or carbon fibres) are related to their low density, renewability and low energy consumption and carbon dioxide emissions. However, these properties are not automatically sustainable and environment friendly. A better evaluation of the significant stages of the entire manufacturing process of the material during the process of conversion of natural fibre and fabrics into the tape, plasma infusion, impregnation and moulding process is necessary to make an informed judgment about the environmental impact on a product through life cycle assessment technique, and mechanical property. The mechanical properties (such as tensile strength and stiffness) of natural composites are effectively improved by compatibilisation of the fibre/matrix interphase. The most critical factor limiting the properties of the composites lie in the intricate structure of the fibres themselves, after the interfacial strength is optimised, the internal fibre structure becomes the weakest point [62].

1.3 Background knowledge

In 2014 a project to develop natural fibre flax/Polylactic acid (flax/PLA) was launched by UK-BIOCOMP to transform yarn flax/PLA and flax/Mapp fibre in to the fabric. However, it is timely to consider whether the claimed benefits of the materials can be justified. The long-term aim of this study is to carry out a quantitative and comparative Life Cycle Assessment (LCA), by the University of Hertfordshire(UH), of natural fibres compared such as Flax , polylactic acid and maleic anhydride polypropylene (MAPP) with glass fibres as a reinforcement for polymer composites, to establish the most sustainable option [63]. As new composites systems have been developed for natural fibre as reinforcement on energy consumption (leading to carbon emissions), and new applications found, a new requirement for test method development, by University of Hertfordshire, has continually evolved [63],[64] . The project goal was to establish new products and value opportunities to start being processed by the company. By developing an essential method and technology for converting yarn flax/PLA and flax/MAPP into composite tape material and SimaPro software was used to collect data. The electricity, carbon dioxide emissions and environmental impact were evaluated. The percentage of flax, PLA and MAPP fibre during the process of conversion varied when commingled into the flax tape and the average production 25 g/m and width 180 m. For instance, two material (flax/PLA) was blended at some percentage to produce a composite material tape unit directional which was 240 m long and was suggested to keep a regular thickness. The machine was set up at 3-4 m/min, and lamination occurred at an elevated temperature of 160-170⁰ C. The energy consumption estimated at 4.4 MJ/h. This study combined analysis of both process and economic input-output to capture direct electricity use and carbon dioxide emissions during the production through life cycle assessment. It will support the choice of alternative material options for use in the automotive, aircraft, marine and construction industry, and points to opportunities for future research about a mechanical and physical property of composite materials. The second process is to transform tape flax/PLA into fabrics, and the average production is 180 g/m² and by joining two narrow tapes for results of 340 mm wider .Therefore, market demand for environmentally friendly products is growing and eco-efficiency broadly accepted as one of the most promising strategies towards sustainable development in answering the global ecological challenges. One strategy to meet this ambitious area is the development and the use of new materials. So, UK BIOCOMP has innovated and analysed a new advanced composite material to contribute to this environmental challenge. The usage of Yarn Flax/PLA associated with different manufacturing process was converted into tapes and fabrics to meet an eco-design

initiative for introducing environmentally friendly natural advanced composites materials. Moreover, the natural composite material flax tape and fabric will follow further development tests such as plasma infusion technique, for around 30 seconds into a chamber to improve mechanical property of the material, prepreg line process with impregnation of resin and later compression moulding into the component and mechanical properties test. The selection of good blends will give us better mechanical properties and some advantage such as good fibre control, high quality tape, uniform fibre placement, improve package quality, and lower energy consumption.

1.4 Aim and Objectives

This project aims for the analysis of the LCA GtG processing of natural fibre reinforcement composites, based on mechanical properties, to select the best combination of materials. The focused approach is to identify, measure, document and interpret the environmental impact of manufacturing natural fibre composites. Hence, the project integrates the following list of objectives.

- 1- Develop an understanding of the production of the composite materials flax/PLA tape and triaxial glass fibre.
- 2- Implement a method to collect primary data, during production of composite flax/PLA tape and triaxial glass fabric (Electricity and carbon dioxide emissions), using Ecoinvent software.
- 3- Evaluate the compression moulding process of the composite flax/PLA tape and triaxial glass fabric.
- 4- Using SimaPro 8 life cycle assessment to produce the manufacturing process tree of fibre in to composite tape, triaxial fabric and composite materials to estimate the environmental impact.
- 5- Investigate the mechanical property of the new composite materials.
- 6- Investigate the energy required to produce a natural fibre composite with an increased thickness that may generate the similar mechanical properties rigidity of the targeted Glass Fibre/Poly-Propylene composites.

1.5 Project plan

The research is established in two parts: Life cycle assessment and mechanical properties, as shown in Figure 1. The proposed research will use standard LCA methodology to examine the production and applications of the natural fibres in comparison to glass fibre in their composites. The project involves collaboration with an industry partner by implementing a method to evaluate the energy consumptions, environmental impact of the transformation of raw materials in to composite tape and triaxial fabric through manufacturing processes, end-users and eventually in the materials recycling and waste. This LCA project will concentrate more on the post-production events of raw material selection and characterisation as part of designs for auto/building and construction/aerospace. They will focus on prepregging process/production, part assembly, end-user operation, and more importantly, the waste recycling/incineration and disposal management. The management of Green House Gas (GHG) emissions, and assigning the contribution to climate change as a basis for the Carbon Footprint concept will also be exploited using BSI PAS2050 2008 and ISO14062. The second part is built on the mechanical properties of the new material.

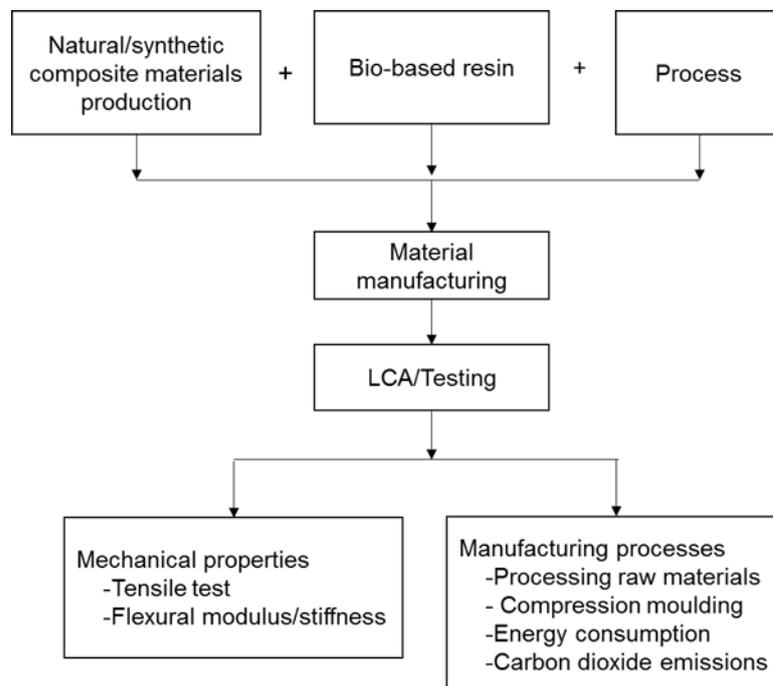


Figure 1: Schematic illustrations on the research of key deliverables. Natural and synthetic material fibre is transformed into fibre and then in to composite material associated with the resin matrix. The process uses energy consumption, and carbon dioxide is produced during manufacturing. The composite material will be tested through mechanical properties to estimate the tensile and flexural test.

The UK BIOCAMP project has developed an innovative family of reinforcement products based on highly aligned natural flax fibres and some of which will be used for sample analysis. The new reinforcements, offer a unique combination of low weight, good vibration damping and sustainability, and are targeting applications in the automotive and sporting goods sectors. Compared to existing woven flax reinforcement, these next-generation materials have improved mechanical properties while being of lower cost. The high-performance flax reinforcements can be supplied as tapes in widths of up to 170 mm, or as full-width non-crimp fabrics. They can also be blended with a high ratio of thermoplastic fibres for direct consolidation.

The life cycle assessment applied to the whole project has been following the British standard ISO 14040:2006 to estimate the global warming potential (GWP) for product development. Therefore, LCA will follow each step of the production by getting access to a UK-Composites partner. Those partners are Tilsatec for natural and thermoplastic aligned and spread into tapes, Henniker for plasma treatment of tapes, Formax for tapes converted into fabrics, Net-composites for materials formed into composites and tested and finally Axon Automotive for final materials used in automotive applications.

The LCA project at university of Hertfordshire on natural fibre (NF) composites, was part of the UK-BIOCAMP initiative, investigated the gate-to-gate LCA, such as energy consumption (MJ/kg) and environmental impact (kg CO₂ /kg Mat.), of natural fibre composites, based on a mechanical property such as test their modulus. Hence, this LCA work has been focusing on the development of the natural fibre composites, to demonstrate the competitiveness of the novel natural fibre materials regarding enhancing the manufacturing process and reducing energy consumption and environmental impact, while retaining product performance.

The LCA outcomes may allow natural fibre composites to be positioned well to improve the growth of an existing UK composites supply chain, when competing with conventional high-energy consumption materials, with an environmentally sound and solution for a range of structural and non-structural applications.

1.6 Thesis contributions

Outcomes from my work, contributions to the natural fibre industry and research.

1. Methodology to combine two fibres (flax and PLA) or (flax and MAPP) to form a composite tape fabric.
2. The design and methodology to implement life cycle assessment to collect data during manufacturing.
3. Implementation to manufacture the composite tape fabric into composite materials with resin matrix (impregnation, compression moulding).
4. Contribution to evaluate the mechanical properties of the composite material tape to find the best combination of flax/PLA tape and flax/MAPP tape fabric.
5. The evaluation of the energy consumption, of the transformation of flax and PLA fibre, in to composite flax/PLA tape fabric and glass fibre tow in to the triaxial fabric.
6. The evaluation of the energy consumption and carbon dioxide emissions of the compression moulding of composite flax/PLA tape and the triaxial glass fabric.
7. Simulation of the manufacturing of the production of composite flax tape, triaxial glass fibre using Simapro 8 LCA, to develop a process tree to determine the environmental impact during production.
8. Theoretical approach to expand the thickness of the new composite materials tape fabric using compression moulding, to generate similar mechanical properties like other materials such as composite glass fibre .This increases the thickness of the composite material which will improve the overall mechanical properties.

The result for the mechanical properties is found by using a collaboration partner to estimate the tensile strength and flexural modulus of the composite materials, tape and glass fabric.

1.7 Conclusion

Material development has generated more and more interest over the Centuries, for industries application. Recently, with the environmental impact, the natural material was developed to produce new friendly renewable material and biodegradable product for industry application. The natural and synthetic material has been transformed into the fabric for composite use, to overcome some conventional material like iron, aluminium and steel. Life cycle assessment was implemented on this study to evaluate the environmental impact during raw materials extraction and end life. Therefore, during their manufacturing process of the production of natural and synthetic material for composite applications, raw materials were selected through a different method; thus, energy and carbon dioxide were produced. The outcome of passing through all these processing stages resulted in a composite material with a resin matrix, the composite material properties determined for their characterisation.

Chapter 2: Literature survey

The literature shows the development and progress of natural fibre for engineering applications. It has revealed a brief history and applications of natural fibres such as flax and PLA compared to some synthetic fibres. The chapter presents some development of advance in manufacturing natural composite tape. Different software is presented and discussed to evaluate the development of natural fibres through the manufacturing process. Simapro LCA is an industry standard software developed to assess advanced manufacturing through material production until the end of life. The manufacturing and material processing was set out in this chapter to show the composite material development and how it was produced, while presenting the embodied energy and carbon storage yield for each operation of the development of composite materials. The method used to measure the characteristics were presented to evaluate the mechanical properties of the composite material products, for a better improvement based on the manufacturing method and energy consumption.

2.1. Implication of natural fibre composite in industry

Ecological concerns have resulted in an increased interest in the use of natural materials; with issues such as recyclability and environmental safety are becoming increasingly important in the development of this product. There is an increasing demand from automotive companies for materials with sound abatement capability as well as reduced weight for fuel efficiency. Natural fibres possess excellent sound absorbing efficiency, are more shatter resistant and have better energy management characteristics than glass fibre reinforced composites. Natural fibre composites are also claimed to offer environmental advantages such as reduced dependence on non-renewable energy/material sources, lower pollutant emissions, lower greenhouse gas emissions, enhances energy recovery, and end of life biodegradability of components [46]. Glass fibres used for composites have density of 2.6 g/cm^3 and cost \$1.3 and \$2.00/kg [46]. In comparison, flax fibres have a density of 1.5 g/m^3 and cost between \$0.22 and \$1.10/kg in Appendix B, section 2B [46]. In automotive parts, such composites not only reduce the mass of the component but also lower the energy needed for production by 80% [65]. A complete calculation of the potential weight reduction requires a component-by-component analysis that minimizes weight given the functional requirements, geometry, and material properties of each component [66]. The variation in the properties of natural fibres composite is another important aspect that has to be considered in these applications such as impact damage tolerance is the key design issue and weight saving.

The use of natural fibre-reinforcement composites in engine components are still in the early stages of development. Fatigue loads at very high temperature poses the most significant challenge in these applications [67]. Developments of high-temperature polymers would greatly enhance the potential for composite usage in this area. The automotive industry gives a long list of presumed benefits of natural fibre composites, which includes the general reasons for the application of natural fibres are [68-71]:

- Low density: which may lead to a weight reduction of 10 to 30%.
- Acceptable mechanical properties, good acoustic properties.
- Favourable processing properties, for instance, low wear on tools.
- Options for new production technologies and materials.
- Favourable accident performance, high stability, less splintering.
- Pleasing Eco balance for part production.
- Desirable Eco balance during vehicle operation due to weight savings.
- Occupational health benefits compared to glass fibres during production.
- No off-gassing of toxic compounds (in contrast to phenol resin bonded wood and recycled cotton fibre parts).
- Reduced fogging behaviour.
- Relatively easy recycling
- Price advantages both for the fibres and the applied technologies.

Obviously, the production and application of natural fibre reinforced parts also bring along some difficulties [72]:

- For the production of non-woven: presence of shives, dust, very short fibres.
- Uneven length distribution and uneven decortication of the fibres (especially for non-woven).
- Irreproducible fibre quality combined with availability.
- Variations in non-woven quality and uniformity due to fibre quality variation.
- Moisture sensitivity, both during processing and during application.
- Limited heat resistance of the fibres.
- Specific smell of the parts.
- Limited fire retardancy.
- Variations in quality and uniformity of produced parts.
- Possible moulding and rotting.

Apparently, the total balance of properties comes out positive, since in ever more new models, natural fibre reinforced composite parts are applied.

The natural composite fibre were utilised in the early years of the composites industry, including flax and hemp fibres, for the bodywork of a Henry Ford car in 1941 [73] .

To achieve the fuel efficiency requirements for Henry Ford, automakers developed new strategies and advanced technologies to improve engines, aerodynamics and vehicles weight. Because vehicle weight reduction is the most effective means for improving fuel economy and reducing energy consumption [74]. Moreover, the body of the East German "Trabant" car (1950-1990) [75, 76], which was one of the typical examples of the application of natural fibres embedded in a polyester matrix to produce a lighter car which was affordable for the passengers [75].

One of the first large application of natural fibre composites materials started in the USA in 1983 [77, 78]. American, Woodstock (Sheboygan, Wisconsin), began producing automotive interior substrates using Italian extrusion technology. Polypropylene with approximately 50% flax was compounded in-line and extruded into a flat sheet that was then formed into various shapes for interior automotive applications [77, 78].

In the early 1990s, Advanced Environmental Recycling Technologies (AERT, Junction, Texas) and a division of Mobil Chemical Company (Winchester, Virginia) began producing solid wood-plastic composites consisting of approximately 50% flax fibre in polyethylene [79]. These composites were used as deck boards, landscape timbers, picnic tables, and industrial flooring [79, 80].

In 1993, Andersen Corporation (Bayport, Minnesota) began producing wood fibre reinforced polyvinyl chloride (PVC) sub sills for French doors [81]. These components typically contain 40% wood in PVC extruded to net shape [81]. Further development led to a wood-PVC composite window line [82].

In 1996, a few U.S. companies that specialise in wood or natural fibre plastic composites began producing a pelletized feedstock for the wood-plastic composites industry [77]. These companies provide compounded pellets for many processors who do not do their compounding [77].

The use of natural fibre in composites applications is being investigated intensively in Europe and UK [15]. As a result, a number of technologies and material combinations are used by the different producers. The major part of the technologies is based on the application of the natural fibres, needle punched, non-woven. The non-woven can be impregnated or sprayed with a thermosetting synthetic binder, for instance, polyester or polyurethane, and then compression moulded in a hot press into the desired shape [72]. The nonwovens can also be impregnated with polypropylene (PP) by means of a travelling extruder, after which they are covered with a second non-woven and compression moulded in a belt press [83]. The final product is then produced by stamping [83, 84]. A third commercially used option is the application of a hybrid non-woven consisting of flax fibres mixed with PP fibres, which can be moulded directly into shape in a hot press [72].

There is a clear trend towards diminishing use of thermoset and increased use of thermoplastic binders. In Germany and Austria in 2000 circa 45% of the produced natural fibre composites [85] were still produced with a thermoset binder, in 2001 and 2002 this figure had diminished to only 22 to 24% [11]. The increasing use in thermoplastic binders is driven by their easier processing characteristics as well as the existence of fogging problems caused by some of the thermoset binders. Another trend that has come up since 2001 is the increased use of injection moulding technology for the production of natural fibre reinforced parts, although up till now this technology is not yet used for flax [86].

Although the flax fibre reinforced composites are often quoted to be developed originally to replace glass fibre reinforced materials, it turns out that at least in the German and Austrian car industry- the thermoplastic natural fibre reinforced compression moulded parts mainly replace wood fibre filled thermoset systems. The use of wood fibre filled composites by the German and Austrian car industry has decreased from circa 60 tonnes per year in 1996 to circa 35 ton per year in 2001 [69]. The advantage of the use of longer natural fibres instead of wood fibres are found in the achievement of significant weight reduction (20% for the door panels of the Mercedes- Benz E-Class), and the improvement of the mechanical properties, important for passenger protection in the event of an accident [87]. Furthermore, the flax-sisal mat used by Mercedes can be moulded in complicated 3-dimensional shapes, thus making it more suitable for door trim panels than the previously used materials [87].

In cars in which natural fibres are employed, presently 5 to 10 kilos natural fibres (flax, hemp, jute, etc.) per car are used. If the total European car industry would employ natural fibres, this would mean a market potential for circa 80 to 160 tonne per year of natural fibres for compression moulded parts in cars. the consumption of natural flax fibre in the automotive industry which was 2,100 tonne in 1996 had increased to 20,000 tonne in 2002 [15, 88]. Therefore, many automotive components are now produced on natural composites, mainly based on polyester or polypropylene and flax fibres [15].

In an exciting research Plackett, Andersen, Pedersen, and Nielsen [89] used commercial L-Polylactide which was first converted to film and then used in combination with jute fibre mats to generate biodegradable composites by a film stacking technique [89]. Degradation of the Polylactide during the process investigated whilst using size exclusion chromatography [89]. The tensile properties of composites produced at temperatures in the 180–220 °C range were significantly higher than those of Polylactide alone [89]. Examination of composite fracture surfaces, using electron microscopy, showed voids occurring between the jute fibre bundles and the Polylactide matrix in some cases [89].

Size exclusion chromatography revealed that only minor changes in the molecular weight distribution of the Polylactide occurred during the process [89].

Researchers have also designed novel rubber bio composites by using a combination of leaf and fruit fibre in natural rubber [89]. The incorporation of sisal and coir fibre in natural reinforcement seem to increase the dielectric constant of the composites. These hybrid bio composites have been found to show enormous applications as antistatic agents [89]. In another interesting study, the preparation of composites comprising of waste paper in natural rubber, along with boron carbide and paraffin wax, for radiation shielding applications, was investigated [89].

In an innovative study, a unique combination of sisal and oil palm fibres in natural rubber has been utilized to design hybrid bio composites [89]. It was seen that the incorporation of fibres resulted in increased modulus [89]. Chemical modification of both sisal and oil palm fibres were imperative for increased interfacial adhesion and resulted in enhanced properties [89]. The viscoelastic water sorption dielectric and stress relaxation characteristics were also studied [89].

In another study bio composites were fabricated using a non-woven fibre mat (90% hemp fibre with 10% thermoplastic polyester binder) as reinforcement, and unsaturated polyester (UPE) resin as well as blends of UPE and functionalized vegetable oils as the polymer matrix [89]. All composites were made with 30% volume fraction of fibre, which was optimized earlier [89]. The structure-property relationships of this system as well as the thermo-mechanical properties of these composites, were measured [89]. The notched Izod impact strength of bio composites, from bio based resin blends of UPE, functionalized vegetable oil and industrial hemp fibre mat were enhanced by 90% as compared to that of the pure UPE-industrial hemp fibre mat composites [89]. The tests also showed an improvement in the tensile properties of the composite as a result of the incorporation of the derivative vegetable oil [89].

The design and life cycle assessment of green composites have been exclusively dealt with by Baillie [89]. Green composites have been used effectively in many applications such as mass-produced consumer products with short life cycles or products intended for one time or short time use before disposal [89]. Green composites may also be used for indoor applications with a useful life of several years [89]. The reinforcement of bio fibres in green composites has highlighted by Bismarck [89].

The incorporation of several different types of fibres into a single matrix has led to the development of hybrid bio composites [89]. The behaviour of hybrid composites is a weighted sum of the individual components in which there is a more favourable balance between the inherent advantages and disadvantages [89]. Also, using a hybrid composite

that contains two or more types of fibre, the advantages of one type of fibre could complement what is lacking in the other [89]. As a consequence, a balance in cost and performance could be achieved through proper material design [89]. The term bio composite is now being applied to a staggering range of materials derived wholly or in part from renewable biomass resources.

A European project call Bio-comp for the composites renewable resources for future product design for engineering applications requires resource saving, variability in properties and functionality, light weight, low costs and eco-efficiency in product life cycle [90]. The bio-composite partner was consisted of European countries developing natural fibre with furan resin for the automotive industry [90]. These requirements for new bio composites can be met using natural fibres, wood extraction constituents and biopolymers to supply branches of mass consumer goods, automotive and electronic industries to be demonstrated by model products [90]. The EU research project BIOCAMP investigated the development of engineering thermoplastics, with matrices lignin and biopolymers polylactide, polyhydroxy-butyrates and starch and thermosets with furan resins and crops oil derivatives [90]. The objective is to up-grade and use raw materials from traditionally industrial sectors of wood (wood powder and fibres), textile and pulp and paper (lignin, hemicellulose and cellulose fibres) industries as well as new biopolymers [90]. The application of bio-composites which have to show its performance by test samples, model products and prototype demonstrators [90]. This includes "product engineering" to achieve the needed specifications [90]. The procedures to derive a desired products from material data, process parameters are the same as for synthetic plastics [90]. These procedures require the use of the material data in relation to the requested specifications and the related processing parameters of the machines and the recommendations and limitations of tool construction [90]. The development of natural fibre was used comprehensively to improve the car industry for petrol efficiency and energy saving. But recently, more implementation was to develop production of advanced light weight natural composite tape fabric before blending with resin. The new composite tape had not been developed on previous research.

2.1.1 Advance natural composite materials

The production and application of bio composites are remarkable achievements to replace conventional non biodegradable petroleum-based materials [91]. BIOCOMP developed new natural composite materials by transforming flax and PLA into composite flax/PLA tape for automotive application. Flax/PLA has followed different tests to improve the mechanical properties, such as plasma infusion, to improve the strength of the new composites materials and physical properties such as thermal analysis. Biodegradable epoxy resin was developed for bark cloth reinforced green epoxy composites with a view to an application of automotive instrumental panels [92]. Reinforcing polymers with fibres has been an effective way to replace standard materials in many industrial applications. However, people must ask themselves about what to do with these materials when the materials' lifespan ends [93]. The development and brief history of natural fibre in industry application are presented in Table 1.

Table 1. Consumption of natural fibre in the car industry in the USA, UK and EU (1941-2016). The development and combinations of natural hybrid biocomposites fibre and applications for the industry to reduce the use of synthetic material.

Dates	Development of natural fibre	References
USA 1941	Flax/Hemp for the bodywork of Henry Ford car	[73]
German(1950-1990)	Flax embedded in polyester matrix(Trabant car)	[7],[75, 76]
USA 1983	Flax/Polypropylene transform into a flat sheet	[77, 78]
USA 1990	Flax/polystyrene into solid composite materials	[79, 80]
USA 1993	Flax/ polyvinyl chloride into a flat sheet	[81, 82]
USA 1996	Flax/plastic into sheet and pallets	[77]
EU 1996-2002	Flax/Polyester or Polypropylene for parts	[15, 88]
Hybrid bio-composite 2004	Combination Sisal and Oil palm fibres Non-woven fibre mat and thermoplastic polyester binder in natural rubber. Waste paper in natural rubber along with boron carbide and paraffin wax, for radiation shielding applications.	[89]
Project BIOCOMP EU/UK 2005	Novel rubber using leaf and fruit fibre in natural rubber incorporation of sisal and coir fibre in natural reinforcement to form hybrid bio-composites.	[89]
BIOCOMP EU/UK 2014-2017	Flax/PLA and Flax/MAPP into fabrics tape for automotive component (Axon Automotive)	UK-BIOCOMP

The recent study on the various aspect of cellulosic fibres and bio composite are finding applications in many fields ranging from construction to automotive industry [90]. Durability and reliability testing will need to develop to account for the behaviour of natural fibre composite materials. A greater understanding of natural fibre composites and their behaviour in various environments is required to justify the inclusion of these materials and their assembly processes in new components [94, 95]. The increased awareness of the importance of environmental protection and the possible impacts associated with products has grown interest in the development of methods to understand better and address these impacts. One of the techniques used for this purpose is life cycle assessment (LCA) [96]. There is nothing actually new about polymer recycling nowadays, but there are many researchers investigating better outcomes in composites and nanocomposites production and recycling [93]. This chapter will give a concise overview about the main challenges in obtaining natural fibre-reinforced polymer composites [93]. With this information, maybe mankind can figure out better ways to recycle or upcycle these heterogeneous and lasting materials [93]. Or better yet, to achieve for them a sustainable life cycle, from cradle to cradle, because this is the reason why there is no waste in nature [93]. It is possible to combine two fibres to form a composite tape fabric that can be used in automotive applications. The natural composite material was developed to face the challenges of government legislation to meet environmental emissions and end of life recyclability targets, along with growing consumer pressure to use more sustainable products. The composite flax/PLA tape was developed to use in different area of industry such as automotive for example, truck interior, door panel, parcel shelf, boot trim. In recent years many natural composite material such as wood and bamboo was made by combine layer and resin matrices mixture to form natural composite materials. By compression, lamination or vacuum bag, whereas by using a composite flax/PLA fibre tape to form a component with resin matrix to produce hybrid composite flax/PLA tape materials. This production and method will reduce the consummation of wood or bamboo for industry application.

2.2 Brief historic of LCA

A better evaluation of the fundamentals and processes of the life cycle of equipment, such as material production phase or manufacturing phase, is necessary to make a judgement about the environmental characteristics of the material. Life cycle assessment (LCA) is a tool specially developed for assessing the overall environmental burden of a product [97]. Therefore, it offers a systematic view of product and process evaluation by tracking down the primary inputs and outputs of materials and energy, identifying and quantifying the energy and material use and assessing the environmental impact [98].

The first studies to look at life cycle aspects of products and materials date from the late sixties and early seventies and focused on issues such as energy efficiency, the consumption of raw materials and, to some extent, waste disposal [99]. In 1969, for example, the Coca-Cola Company funded a study to compare resource use and environmental releases associated with beverage containers [100, 101]. Meanwhile, in Europe, a similar inventory approach was being developed, later known as the 'Ecobalance'. In 1972, in the UK, Ian Boustead calculated the total energy used in the production of various types of beverage containers, including glass, plastic, steel, and aluminium [102, 103]. Over the next few years, Boustead consolidated his methodology to make it applicable to a variety of materials, and in 1979, published the Handbook of Industrial Energy Analysis [104].

Initially, the use of energy was considered a higher priority than waste and outputs. Because of this, there was a little distinction, at the time, between inventory development (resources going into a product) and the interpretation of associated cumulative impacts. However, after the oil crisis subsided, energy issues declined in prominence. It was not until the mid-eighties and early nineties that a real wave of interest in LCA swept over a much broader range of industries, design establishments and retailers taking many of them by surprise [104].

In the early 1990s, while advances continued to be made, international and draft standards of the ISO 14000 series were, in general, accepted as providing a consensus framework for LCA. There was considerable confusion regarding how LCA should be conducted [105, 106]. Moreover, in the same year, many industry sectors were proactively meeting requests for data to be used in LCAs. The Association of Plastics Manufacturers in Europe (APME) can be considered the pioneer in making data publicly available [107], but also other industry associations have been actively collecting and providing data [107]. Survey of LCA activity to date, the LCA Sourcebook, was published in 1993 [108]. At the time, LCA was of limited interest outside a small community of scientists, mostly based in

Europe or North America. However, the Sourcebook noted, “their work escaped from the laboratory and into the real world.” Some countries took an early lead. “In the UK,” said David Cockburn of PIRA, “it has been surprisingly fast. Ten years ago there was only one leading practitioner” [108, 109].

The leading basis for all the previous quantification standards is ISO 14040 ;the represent the constitution of LCA in 2006 [110]. Many of the others standards contain significant amounts of ISO 14040/44 contents,with exception of the limited focus of the carbon footprint standards on climate change,all of them reference ISO 14044 as their basis and basically comply with it. Table 2 show a brief historic and improvement of the LCA since 1969.

Table 2.The innovation of LCA to improve materials development. The applications and the development of LCA used by some renowned companies to enhance its’ production process and reduced waste and recycling of their product.

Years	Development of LCA	References
1969	Coca-Cola compared resource use and environment release associated with beverage containers.	[100, 101]
1972	Ian Boustead calculated the total energy used in the production of various types of beverage containers includes glass, plastic, steel and aluminium.	[102, 111]
1979	Boustead published the Handbook of Technical Energy Analysis.	[104, 112]
1990	First ISO 14000 series on LCA was established	[100, 106]
1993	LCA sourcebook was published	[109] [108]
2006	Environment management LCA BS ISO 14040 was established	[110, 113, 114]

Now there are many more academics, consultancies and companies with an in-house capability. While the field continued to progress, the pace has been sporadic. According to a recent report by IMSA and SPOLD 3, the main barriers to greater advances in the LCA field have been a moderate level of experience with LCA, coupled with unfair expectations and “over-advertisement”. The period of disillusionment with LCA, aggravated by a strong sense that many of those using LCA were simply doing so to buttress existing positions, rather than to understand fully and respond to the real issues [104].

2.3 Principle and framework of LCA

Life Cycle Assessment is a methodological framework (defined in the DIN ISO 14040/44) to assess the environmental impacts associated with all the stages of a product's life from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling [115]. The methodology was adopted and standardised by the International Organisation for Standardisation (ISO). The standards ISO 14040/14044:2006 currently provide a reference on principles, framework and terminology for conducting and reporting LCA studies and are internationally recognised and used [110, 116]. All products that are goods or services, have some impact on the environment. This may occur at any or all stages of the products acquisition, manufacture, use and disposal. Therefore, anticipating or identifying the environmental aspects of a product throughout its life cycle may be complex [117]. The purpose to use LCA is to affect business results by helping to save money, reduce risk, communicate product benefits and increase revenue. A standard LCA consists of the four elements presented in Figure 2: Goal and Scope Definition, Inventory Analysis, Impact Assessment and Interpretation. Goal and Scope Definition describes why and how to use an LCA.

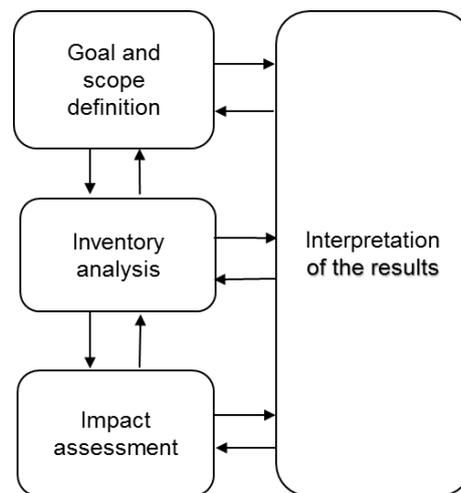


Figure 2: The four-component of an LCA study is goal and scope; inventory analysis; impact assessment and interpretation. The four elements define and describe the product, process or activity. This is very important part in the LCA , as it determines and guides the choices to be made in the other phases of the study [118].

The goal and scope definition phase is to standardise the life cycle assessment, the purpose of the assessment is established and decisions are made about the details of the product system being studied [119]. The goal and scope are defined at the outset of the study, before any data are collected [119].

The outlined methodology is defined by the international standards for Environmental Management Systems [105]. There are a variety of assessment methods and software which can be applied to the LCA problem, including CML92 [120], Critical Surface-Time (CST95) [121], Eco points [122] Eco-indicator 95 [123], SimaPro [124] and Ecoivent [125]. Despite a general descriptions of some of the life cycle assessment methodology and software apply to it are given in Table 3. Some of them similar to ecoivent are a based to support the data collection.

Table 3: Description of LCA methodology and Software. The table shows the variety of assessment methods and software descriptions that can be used to assess the LCA of a raw material production until the end of life.

Method	Description and software	Origin
CML 92	This is one of the first LCA methods available which includes characterisation and normalisation. This is claimed to include the most relevant multi-score valuation methods in LCA.	Centre for Environmental Studies (CML), the University of Leiden in 1992
Critical Surface Time (CST 95)	This method provides a characterization of toxicity, together with a clear separation of scientific and societal weighting in the evaluation step. The impact categories considered are human toxicity, terrestrial ecotoxicity, aquatic ecotoxicity, global warming, photochemical oxidation, acidification, eutrophication and energy consumption.	Olivier Jolliet & Pierre Crettaz, EPFL Lausanne in 1997
Eco points	Environmental impacts are evaluated directly, and there is no classification step. The Eco- Points methods have been accepted as a useful instrument, but the lack of a classification step is also regarded as a disadvantage - only a very limited number of impacts can be evaluated. Eco-points Method was/is widely used in Switzerland and Germany. It is also employed in UK, Norway and Netherlands.	Developed in Switzerland
Eco-indicator 95	The evaluation method for calculating the Eco-Indicator 95 strongly focuses on the effects of emissions on the ecosystem. The targets values are related to three types of environmental damage: <ul style="list-style-type: none"> • Deterioration of ecosystems 	Developed in a joint project carried out by companies, research institutes and the Dutch government.

	<ul style="list-style-type: none"> • Deterioration of human health • Damage to mineral and fossil resources. 	
Ecoinvent	Contains up-to-date Life Cycle Inventory (LCI). The data with more than 4'000 LCI datasets in the areas of agriculture, energy supply, transport, biofuels and biomaterials, bulk and speciality chemicals, construction materials, packaging materials, core and precious metals, metals processing, ICT and electronics as well as waste treatment.	Developed by Swiss Centre for Life Cycle Inventories.
SimaPro	<p>The LCA Simapro-software allows to model products and systems using regular features such as parameters, Monte Carlo analysis and integrated eco-invent database. It also has applications such as:</p> <ul style="list-style-type: none"> • Carbon footprint calculation • Product design and eco-design • Environmental Product Declarations (EPD) • Environmental impact of products • Environmental reporting (GRI) • Determining of key performance indicators 	Developed and supplied by PRé Consultants in Netherlands.

We developed more understanding of the function of SimaPro software LCA to better produce a simulation and analyses different part of the software LCA through simple example. During this initial stage, decisions are made regarding the definition of the functional unit, system boundaries, allocation procedures, choice of impact categories to be studied and methodology of the impact assessment. The Inventory Analysis quantifies all inputs and outputs of a product system and thus involves data collection and calculation procedures [13]. Impact assessment translates the inventory data into contributions to environmental impact categories and interpretation is the final step of LCA [126]. Therefore, LCA will use some method describe above to obtain useful secondary data. The three connection of LCA (Table 4) which are Resource exploitation and manufacturing (Cradle to gate), disposal/Recycling and usage (Gate to Grave) and Production (Gate to Gate). We focus on the gate to gate to establish the manufacturing process and electricity use for a single production phase.

Table 4: Different types of life cycle assessments and system boundaries were evaluated to show the process [126]. Every kind of LCA defines the production method and applies to a specific area of product development [127].

LCA	Boundaries
Gate-to-Gate	-Production
Gate to Grave	-Usage -Disposal/Recycle
Cradle to gate	-Resource exploitation -Manufacturing

In this study, the life cycle energy of natural fibre composite manufactured, using a different process, can be analysed. Therefore, it is critical to estimate how much energy consumed during the lifetime of the composites compared to other materials. In particular, we can evaluate a potential for composite materials to save energy in automotive applications. The energy analysis based on manufacturing phase which involves energy consumption (electricity and CO₂e) [128]. The type of life cycle assessment (LCA) used for this study is the gate to gate which only represents a limited number of process stages, from factory door into factory door out there by excluding prior and succeeding process or activities of a single company [129]. Gate to gate: implies the processes that take place in the production phase, to establish the ecological impact for a single production step [129].

Details of benefits to use LCA are:

- Determine the strategic risks and environmental optimisation potentials of products at an early stage.
- Identify the magnitude and relevance of each individual step within a products life cycle. Which stage causes the greatest environmental burden?
- Obtain solid information regarding the environmental impacts of your organizations processes and products to improve external communications with customers, suppliers and other stakeholders.
- Solidify your need for ecological action and identify the most efficient measures for adjustment.
- Spur environmental innovation by implementing Life Cycle Assessments.
- Generating understanding of Life Cycle Thinking and integrate it into day-to-day business on all levels.
- Improve communication lines with political decision makers and public authorities with the help of a LCA

2.3.1 Application of life cycle evaluation of energy used to produce flax fibre

The LCA study involves a thorough inventory of the energy and materials that are required across the process to produce flax fibre, and calculates the corresponding emissions to the environment.

2.3.1.1 Production of flax

The typical production cycle of flax fibres [130], are:

- Tillage: the preparation of land for cropping by ploughing or similar operations. Conventional tillage is preferred in flax cultivation which is primary tillage followed by early spring tillage and planting. Some growers have trialled No-till methods with no significant change in flax yield [131].
- Drilling (planting) the seed: this usually occurs between the end of February and early April in Belgium, France and the Netherlands or at the beginning of April in Northern Ireland (NI). Flax is planted in narrow rows (15-20 cm apart) using similar equipment to cereals. Optimum seed depth is 2.5-4.0 cm deep, and optimum seeding rates are 35-50 kg/ha [130]. For flax in UK, the suggested levels of fertiliser are: nitrogen (N) - 40 kg/ha, phosphorus (P) as P₂O₃ - 50 kg/ha and potassium (K) as K₂O - 50 kg/ha [132].
- Weed control: Flax is a poor competitor with weeds, and it is essential to minimise weeds to avoid contamination of the scutched (i.e. decorticated) flax fibres. Herbicides are applied to achieve this.
- Plant growth: the life cycle of the flax plant consists of a 45 to 60 days vegetative period, a 15 to 25 days flowering period and a maturation period of 30 to 40 days.
- Desiccation: Glyphosate is typically applied 10-14 days after a full flower, at about mid-July in NI. Glyphosate is only used where stand retting is adopted followed by direct combine harvesting of the crop. Chemical desiccation or drying of the harvest has numerous advantages over field retting such as earlier harvesting, elimination of the need for swathing, reduced combining time, less wear on machinery.
- Harvest: by either combine harvester or pulling, in August/September.
- Rippling: the removal of flax seed capsules by drawing pulled stems through a coarse steel comb.

- Retting is defined for flax as the “subjection of crop or deseeded straw to chemical or biological treatment to make the fibre bundles more easily separable from the woody part of the stem. Flax is described as water-retted, dew-retted or chemically–retted according to the process employed [133]. Enzymes may be used to assist the retting process, but the termination of the retting process may be a problem and failure to achieve this can result in reduced fibre properties [134]. Pre-harvest retting of flax with glyphosate applied at the midpoint of flowering depends on uniform desiccation of the entire stem, and it is hard to achieve during a dry season [135]. As in dew-retting, stand-retting of the desiccated flax in the field relies on microorganisms and is dependent on the vagaries of the weather [135].
- Decortication is the mechanical removal of non-fibrous material from retted stalks or ribbons or strips of the stem to extract the fibres. For flax, the process is usually referred to as “scutching”. They can be achieved by a manual operation, hammer mill, inclined plane with fluted rollers or willpower.
- Hackling is the combing of line flax to remove short fibres, align the remaining long (line) fibres and also remove any extraneous matter (shive).
- Carding is defined as “the disentanglement of fibres by working them between two closely spaced, relatively moving surfaces clothed with fine wire, pins, spikes or saw teeth” [133].
- Spinning is the drafting [decreasing the mass per unit length] and twisting of natural (or human-made) fibres for the production of yarns or filaments.

Therefore, the yarn fibre is ready for a next stage production to be transform into fabric, by following some method such as weaving, felting, knitting, and crochet.

2.3.1.2 Energy use in flax fibre

In the fibre production process, energy used to power agricultural machinery, fibre processing equipment and to produce and apply fertilisers and pesticides, are the primary sources considered in the context. The use of farm machinery adds to production costs and the consumption of fuel. Energy consumption used by the machine is calculated according to the fuel consumption for various agricultural operations, where the energy density of diesel fuel is taken to be 34.92 MJ/l [136]. Flax fibre yield per hectare is assumed as 972 kg of scratched long fibre (6000 kg of dry, green stem) [137]. The Stem review lists fertiliser manufacture as the fourth most energy-intensive industry consuming 13.31% of total costs (after electricity production and distribution: 26.70%, gas distribution: 42.90% and refined petroleum: 72.83%). 26.70%, gas distribution: 42.90% and refined petroleum: 72.83%). Globally around 1.3% of all energy produced is used for fertilisers [138].

2.3.1.3. Flax processing operations

After the crop is harvested, the first stage of flax fibre processing is retting. Rippling, which is the removal of flax seeds can be done as a part of harvesting where combine harvesting is adopted. Two methods of retting considered are bio-retting and warm-water retting. Retting is followed by a mechanical process called scutching /decortication. The process consists to break the woody core of the stems into small pieces and separating short fibres from long fibres by beating the broken stem with rotating blades [137]. Decortication followed by hackling, carding and spinning of the fibres. Values of energy consumption for fibre processing operations are given in Table 5.

Table 5. The transformation of raw flax in to flax fibre used different operation. Therefore, energy consumption was estimated for every processing operations [137].

Operation	Energy consumption-MJ/kg
Retting - Bio	0.48
Warm water	0.03
Decortication / Scutching	0.53
Hackling	1.39
Carding	3.94
Spinning	22.9

Energy consumption throughout the production process for flax fibres has been analysed using published data. The total energy consumption to produce 1 tonne of flax scutcher fibre using a conventional system is approximately 2250 GJ, and conservation system is equivalent at 0.96GJ [139]. Therefore, the total energy to produce flax fibre is 29.27 MJ/kg.

The details of specific material and energy flows, emissions and manufacturing processes vary depending on the specific application. However, material flows, energy use, emissions, and environmental impacts over all these stages need to be modelled, inventoried and analysed for a comprehensive life cycle assessment [140] .

2.3.2 Application of life cycle evaluation of energy used to produce polylactic acid (PLA)

The life cycle is performed on a cradle to grave, starting in the manufacture of corn till transformation into PLA by looking the energy consumption. However, Polylactide is a versatile polymer that is made from 100% renewable resources like corn, sugar beets or rice [141]. The main process was developed for conversion of lactic acid into lactide and processes and technologies for purification and polymerization of lactide [142]. There are two major routes to produce polylactic acid from the lactic acid monomer: direct condensation polymerization of lactic acid and ring-opening polymerization through the lactide intermediate. The first route involves the removal of water by condensation and the use of solvent under high vacuum and temperature. With this route, only low to intermediate molecular weight polymers can be produced, mainly because of the presence of water and impurities [143]. The second path: ring-opening polymerization through the lactide intermediate [142].

In the first step of the process, water is removed under mild conditions (and without the use of a solvent) to produce a low molecular weight pre-polymer. This pre-polymer is then catalytically depolymerised to form a cyclic intermediate dimer, referred to as lactide which is then purified to polymer grade using distillation [144]. The purified lactide is polymerised in a solvent-free ring-opening polymerization and processed into Polylactide pellets [145].

2.3.2.1 Production technology of poly lactic acid

One of the most promising biodegradable polymers is poly (lactic acid) (PLA), and PLA can be manufactured from renewable resources, most commonly from corn [146, 147]. Most of the research on PLA composites ultimately seeks to improve the mechanical properties to a level that satisfies the particular applications, where PLA could be a replacement for synthetic polymers like PP [148, 149].

The PLA life cycle stage starts with corn, and the main objective is to decrease the fossil energy use from 54 MJ/kg PLA down to about 7 MJ/kg PLA [150]. The target for greenhouse gases is a reduction from +1.8 down to 1.7 kg CO₂ equivalents/kg PLA [150]. All free energy consumed by biological systems arises from solar energy that is trapped

by the method photosynthesis [150]. The various steps involved in the production of PLA starting with corn growing and ending with the production of PLA granules [150]. After harvesting, the corn is transported to a wet corn mill where the starch is separated from the other components of the corn kernel (proteins, fats, fibres, ash and water) and converted via enzymatic hydrolysis into dextrose. The process consists of fermenting dextrose into lactic acid at near neutral pH. Through acidulation and a series of purification steps the lactate salt, the fermentation broth is then purified to yield lactic acid [143]. The contribution to the gross energy requirement for PLA is 82.5 MJ/kg accumulated for the life cycle from corn growing through the production of ready to ship pellets [151].

The input including Corn growing such as corn seed, fertilisers, electricity and fuel (natural gas, diesel, propane and gasoline) used by the farmer, atmospheric carbon dioxide take up through the photosynthesis process, irrigation water and pesticides. On the output side, emissions such as dinitrogen oxide, nitrates and phosphates were taken into account [151]. The amounts of electricity risen approximately to 28.4 MJ represents the corn feedstock (15.5% moisture) used to produce 1 kg PLA. The renewable energy and defined using the heat of combustion of maize (16.3 MJ/kg corn). This part is fixed and can only be decreased by using less corn. The gross fossil energy consumption (GFEC) is 54.1 MJ/kg of PLA, equivalent to the gross energy requirement (GFR) less the energy embodied in the corn feedstock (calculated as $82.5 - 28.4 = 54.1$ MJ/kg) [151].

The crude fossil energy use (CFEU) estimated to be required for lactic acid production is 26.3 MJ/kg PLA or 49% of the fossil energy used of PLA. The 26.3 MJ/kg is the sum of the gross energy inputs relating to the operating supplies and the waste-water treatment (11.4 MJ) and the electricity and other fuels used in the lactic acid facility (14.9 MJ). Lactic acid production technology improvements. The introduction of an improved lactic acid production techniques is expected to yield greenhouse gas emissions reductions of 0.58 kg CO₂ equivalents per kilogramme of PLA pellets (CO₂-eq. /kg PLA) [151]. They use life cycle inventory data in much the same way that processes economic data is utilised to target and improve key process components [42]. The total energy use to produce PLA is 52.6 MJ/kg and carbon dioxide emission at 27.5 kg/CO₂ [42].

PLA has better mechanical properties than others material such as PP, with a tensile strength of 62 MPa and a modulus of 2.7 GPA, in contrast to 36 MPa and 1.2 GPA for PP. Moreover, PLA can be processed by injection moulding, blow moulding, [152] and film extrusion because the glass temperature of PLA is 50–60 °C and the melting temperature is 168–172 °C [153]. Limited research has been published on the use of SF as filler or reinforcement in the PLA matrix shown in Appendix A, section 13A [153-155].

2.3.3 Application of life cycle assessment of energy analysis of fibre reinforced composites.

The implementation of the life cycle assessment to analyse the energy use for the production of composites materials was estimated using information from the literature. They do not cover the overall transformation and end of life stage, but the processing of material and the manufacturing process to transform raw materials into fibre. Therefore, the energy consumption was assessed for each process to transform raw materials in to fibre tow. In addition to the carbon dioxide emissions and greenhouse gas emissions can be deducted [156]. They will also be used to investigate sustainable material and design for the environmental perspectives.

2.3.3.1 Materials production of fibre reinforced composites

The first stage of the product life-cycle is “material extraction “for natural fibre or similar materials, which involves pulling fossil fuels from the earth [157]. These materials are then refined and separated before producing the input materials for manufacturing. The next step is to call for extraction and production of materials, called “material production”. Materials used (Table 6) in manifold fields have different energy intensities for extraction and production [157].

Table 6: The energy consumption of various materials and resin production. The energy intensities of materials vary depending on technology, methods, and infrastructure [144].

Materials	Energy intensity (MJ/kg)	References
Polymers		
Resin blending	0.1	[158]
Polyester	63-78	[158-161]
Epoxy	76-80	[159, 162]
Furan resin	4.01	[163]
PLA	7.0	[150]
PP	72-112	[161, 164]
Fibres		
Glass fibre	13–32	[164-166]
Carbon fibre	183–286	[167]
China reed fibre	3.6	[168]
Flax fibre	6.5	[169]
Metals		
Aluminium	196–257	[170-172]

Polymer matrices such as thermosetting and thermoplastic polymers are created through energy-intensive chemical processing. The plastic material and resin sector of the

chemical industry alone accounted for 414000 million MJ of energy consumption in the USA in 1998, which amounts to 2.2% of the total energy consumed by USA [173]. Among polymer resins, thermosets including polyester and epoxy resins used in fibre-reinforced composites possess relatively low energy intensities. Since the energy intensities of materials vary depending on technology, methods, and infrastructure, they are in a wide range as shown in the table. For example, glass fibres which are one of the most common basic materials to reinforce plastics, have broadly varying production energy intensities. Stiller compared and analysed several manufactures of glass fibres, PPG, Owens Corning, and Vetrotex [165]. Owen Corning consumed the lowest intensity of 12.58 MJ/kg, whereas Vetrotex had the largest intensity of 32.0 MJ/kg [165]. Besides, even at one manufacturer energy intensities change significantly: Vetrotex plants in Germany consume 32.0 MJ/kg, while Vetrotex International plants use 25.3 MJ/kg [165]. This can be explained in part by economies of scale.

As such, LCA has become a valuable complementary analytical tool when married with the pursuit of cost improvements and helps move the company toward its goal of sustainability in process and operations. Moreover, the analysis increasingly demonstrates that the best cost or environmental performance improvement tactics and strategies yield multiple benefits, all of which are valuable to the company as it seeks commercial market success.

The energy used to produce a variety of materials can be more complex in estimating the energy consumption, depending on the manufacturing process use and the machine set up. The method to estimate the energy consumption is more complex and unstandardized. Polymers from renewable resources can be meaningfully lower in greenhouse gas emissions, and fossil energy uses today as compared with conventional petrochemical-based polymers. Over the longer term, LCA demonstrates that PLA production processes can become both fossil-energy free and a source of carbon credits. This bright future will come only with the significant investment of time, effort and money. A final, significant benefit of LCA is that it can serve as a tool for monitoring return on these investments over time [151].

2.4 Material intensity and advanced composite materials

The advantages of natural fibres over synthetic or human-made fibres, such as carbon and glass, are the low density, low cost, acceptable specific strength properties, biodegradability, and easy of separation [174]. Therefore, the relative sustainability of biocomposites should be observed at all stages of development through life cycle assessment to estimate energy consumption and to improve the process. The relationships between natural fibre properties and resin matrix properties are more complex than those in glass fibre reinforced composites [8]. The objective for replacement of glass fibres in sheet moulding compound by natural fibres in the transportations sector. These products comprise different kinds of bodyworks, like spoilers, funnels, etc. and gain more and more interest by the transportation industry because of their specific properties. An additional benefit of natural fibre reinforcement composites with respect to glass fibre reinforcement composites is its end-of-life scenario. Due to European legislation on waste dumping, natural fibre reinforcements composites exhibit the advantage of being combustible, this in contrast to glass fibre reinforcements composites [175].

2.4.1 Composites manufacturing phase

Composite materials can be manufactured using a wide variety of techniques and matrix (Table 7). The production process for a particular structure will depend on the chosen fibre and matrix type, processing volume, and the geometry of the component. In general during fabrication processes, a significant amount of energy is used to provide heat and pressure necessary for curing, shown in Appendix A, section 6A,7A,8A and 9A [10]. All these issues should be addressed right from the beginning of the development cycle for a component or structure. Different processes to manufacture composite materials have been defined and discussed such as Compression moulding, Prepregging and vacuum infusion for the production of component part.

Table 7: The manufacturing technique is interrelated with other composite parameters. Here the maximum and typical values of various parameters for plant fibre reinforcement plastic (PFRP) are quoted. The values are from the literature referenced [176].

Manufacturing technique	Consolidation pressure(bar)	Fibre volume fraction (%)	Matrix type useable
Compression moulding	Up to 40 bar (typically 20-30)	Up to 85 % (typically 25-50%)	Thermoplastic or Thermoset
Prepregging(with autoclave)	0-10 bar (typically 4-6 bar)	Up to 60 % (typically 35-50%)	Thermoset
Vacuum infusion/RTM	0-4 bar (typically 20-30)	Up to 60 % (typically 25-50%)	Thermoset

The composite manufacturing technique affects the typical achievable fibre volume fraction and porosity. For high composite mechanical properties, high fibre volume fraction and low porosity are desirable. With increasing consolidation pressure, achievable and typical fibre volume fraction tend to increase [176]. This indicates how cooling too rapidly can reduce part crystallinity and carbon dioxide emissions produce through energy consumption and composite materials.

2.4.2. Wet layup

The process of wet layup (Figure 3), consists of placing the fibre on a mould surface in fabric form and manually wet them out with resin. The wet layup is widely used to make large structures, like the hulls of small ships. This process is amenable to high production rates but results in wide variations in quality. In particular, the inability to control the ratio of fibres to resin means that the mechanical properties of the laminate will vary from point-to-point and structure-to-structure [10]. The energy intensities on this process represent energies associated only with processes, but not relevant materials and can be estimated at 19.2 MJ [167]. Therefore the volatile organic compound can get an impact on the environment during impregnation of the resin on the composite materials.

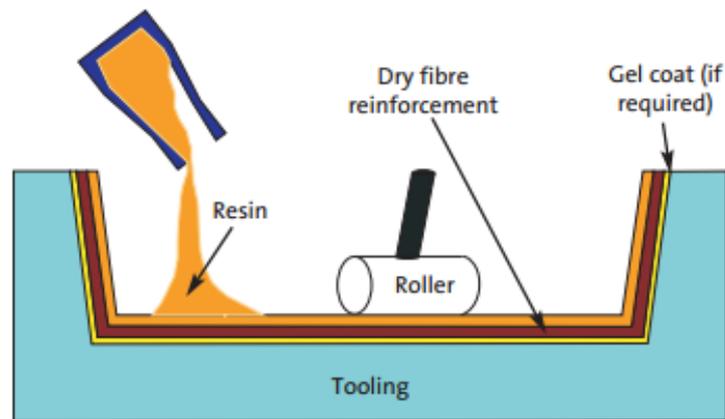


Figure 3: Schematic of the hand-layup fabrication method: a computerised machine cutter can cut layers, and the layers can be superpose on top of the other by a robot, and the resin is sprayed to each layer on the top of each other before to be cured [177].

Depending on availability equipment, the production of part is not constant and may vary during production, if we have to realise the same part or make mass production. It is a simple and low-cost process to achieve different thickness and shape on the same component.

2.4.3. Prepreg layup

In the prepreg process, fabrics are impregnated with controlled quantities of resin before being placed in a mould. Prepreg layup is typically used to make high-quality components for examples for the aerospace industry. This process results in particularly consistent components and structures with a very high mechanical performance. Because of this, prepreg techniques, often associated with sophisticated resin systems, are cured in autoclaves under conditions of high temperature and pressure as shown in figure 4. However, the applications of prepreg layers to a surface is highly labour intensive, and can only be automated for a small class of simple structures [177]. During this process of prepreg production, presented in Figure 4, electricity or gas are used to produce heat and therefore produce carbon dioxide emissions. Energy intensity can be quantified at 40 MJ/kg for this process depending on the method [167]. Then, it is crucial to estimate how much electricity and carbon dioxide emissions are used to provide this type of material.

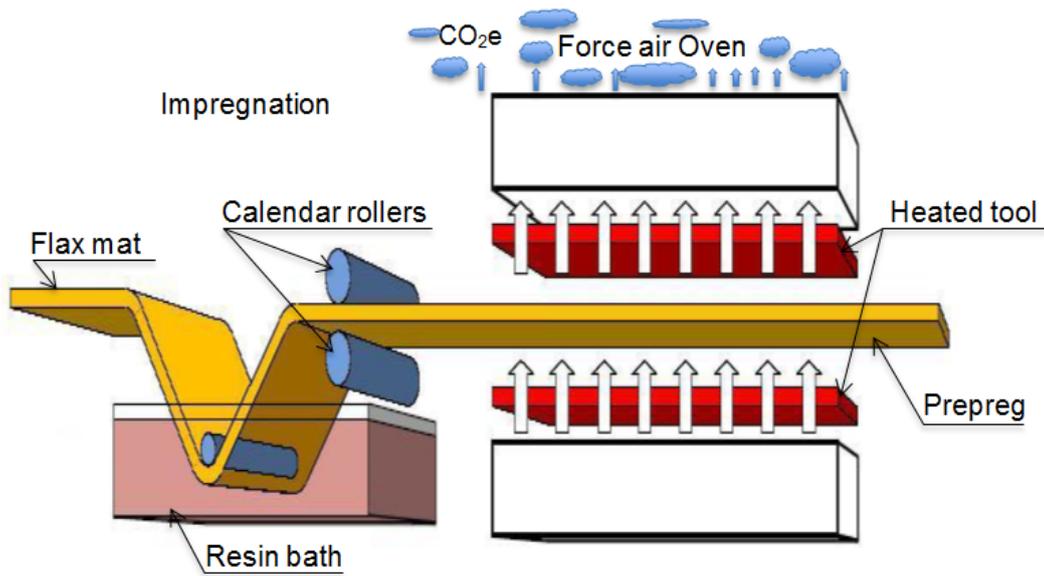


Figure 4: Process of impregnation line of flax and resin matrix. The figure shows us how the flax mat passed through the resin bath and calendar rollers before they were heated to become impregnated. The process is continuously working to impregnate resin on the composite material, at a constant speed [178].

The material passed through a resin basin and between two calendar rollers to reduce the excess of resin by lamination and then through a heater system to be dried and stored. This process improves the quality of impregnation by reducing the inequality of resin during impregnation on composite materials. Therefore, during the production process, the waste of resin is reduced and the impregnate material can be saved for a few days before moulding.

2.4.4 Compression moulding

Compression moulding describes the process whereby a stack of pre-impregnated layers are compressed between a set of matched dies using a great press and then cured while under compression. This method is often used to manufacture small quantities of high-quality components such as crash helmets and bicycle frames. It is tough to make components where the plies drop off consistently within the component, for example, the shape corner [179]. During compression moulding, the material is preheated and placed in a mould cavity that is heated by hot pressure in the press. The mould is closed, the pressure is applied to force the material together in the frame, and heat and pressure maintained until the moulded material has cured [179].

The moulding cycle time on the machine consists on the heating and cooling time ,which depends on the shot size and machine power [180]. The cooling time (tc) in Equation 1, which is largely driven by the square of the maximal wall thickness [180]:

Equation 1: The cooling time (tc) min for compression moulding.

$$t_c = \frac{h^2_{max}}{\pi^2 \alpha} \log_e \frac{4(T_i - T_m)}{\pi(T_x - T_m)} \quad (1)$$

Whereas, h^2_{max} represented the maximum wall thickness of part in mm, T_x recommended part ejection temperature °C, T_m recommended mould temperature °C, T_i polymer injection temperature °C and α is the thermal diffusivity coefficient mm^2/s . As suggested by Lovejoy, the cycle time(t_o) in Equation 2 can be simplified as [181]:

Equation 2: The cycle time (t_o) min for compression moulding process

$$t_o = \frac{h^2_{max}}{\alpha} \quad (2)$$

The cycle time (t_o) show that we have to use the maximum thickness (h^2_{max}) and thermal diffusivity (α) to work out the time for moulding. Table 8 presents some element of the heat transfer on the material that, can be expressed using different formulas and methods, therefore a new composite material's formula can be considered.

Table 8: Quantity dimensions and the unit measurement equation. It is particularly useful when a mathematical equation connecting the different quantities with one another are unknown [182].

Symbol	Quantity	Dimensions	SI unit
c	Specific heat	$L^2 / t^2 T$	J/kg k
k	Thermal conductivity	$ML / t^3 T$	Wm/k
ρ	Density	M / L^3	kg/m ³
k/c_p	Thermal diffusivity	L^2/t	m ² /s

NB: t=time, T= temperature M=mass and L (H) =length

The dimensions are particularly useful when a mathematical equation connecting the different quantities with one another is unknown, or when the mathematical development is very complex. In that case the grouping of various quantities, to form dimensionless numbers, facilitates the most rational choice of research criteria [168]. During

manufacturing of natural fibre composites, heat transfer is involved, but information about the thermal conductivity and thermal diffusivity at the processing temperature is not available [183]. Therefore the thermal conductivity, thermal diffusivity, and specific heat of flax fibre high density polyethylene (HDPE) bio composites were determined in the temperature range of 170 to 200°C shown on Appendix C, section 3C [184]. On this process, CO₂ emissions are produced, and weight loss can be estimated after the composite material part produced and the energy used for this process is around 11.8 MJ/kg [162]. Therefore, moulders should realize how significantly processed conditions can influence the final properties of the component [185]. Temperature, pressure and time are varied depending on the weight of composite materials (Thickness). From the data it became clear that a temperature of 140°C and times varying between 2-6 min gave best results [175]. The duration of the compression moulding step depends on the thickness of the prepreg. The compression moulding process (Figure 7), can have pressures between 3.5 and 14 MPa to produce a component [175]. Higher viscosities made it possible to press at higher pressures [175].

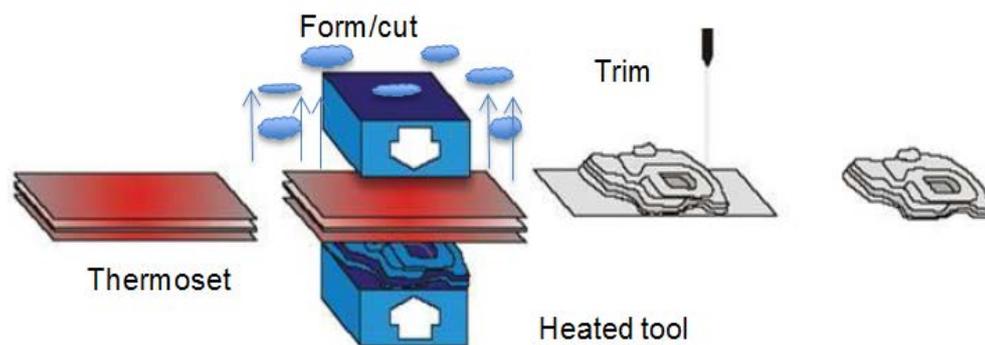


Figure 7: The process to form and cut a component. The compression moulding pressure is used to heat and give a shape of composite materials and trimmer it for a final product, with an excellent surface finish [178].

None of the process described above gives us information about the exact energy intensities and carbon dioxide emissions. Therefore, the power consumption is 11kW depending on the machine and process. Thus, the volume fraction of the materials will have a significant influence on the energy. While fibres reinforced composites have shown potential for automobile parts in the past several decades, the application has yet to be realised on a mass production scale, due to several drawbacks including low production, automation rates, and significant costs. The electricity use for a single process varies depending on technology, methods, infrastructure and area where they are located.

B Van ,H.H.G Smit study the natural fibre reinforcement sheet moulding compound, when the fibre length exceeds 25 mm [175]. The compression moulding step of the SMC-process, which is the final step for the actual product is formed. Temperature, pressure and time are varied. From the data it became clear that a temperature of 140°C and times varying between 2-6 min gave best results. The duration of the compression moulding step depends on the thickness of the prepreg. Compression moulding pressures between 3.5 and 14 MPa were used to set the composite. Higher viscosities made it possible to press at higher pressures. All experiments are carried out using 6 mm flax fibres, unless otherwise stated [175]. Some figures show that increasing the fibres thickness will increase the mechanical properties of the composite. The mechanical properties are to be developed during the moulding process and improving the manufacturing process of the composite materials. By estimating the mechanical properties, we can improve the manufacturing of the composite material.

As expected, in general it can be said that increasing the amounts of fibre and filler will increase the tensile properties [175]. The columns on the left are the E-modulus and on the right the tensile strengths. This figure shows that if we increase the fibre thickness, therefore the mechanical properties will increase. The flexural modulus properties show a similar effect on the increasing of fibre thickness [175]. With increasing fibre and filler percentage, both the modulus and strength increase [175]. When the influence of the fibre is regarded in natural fibre short moulding composite (NFSMC), a rather profound effect is to be observed. Fibre lengths that were used are 6, 13, 25 and 38 mm. We can conclude that the fibre length has a large influence on the flexural properties of the natural fibre short moulding composite [175].

2.5. Manufacturing of fibre reinforced composites

While fibre-reinforced composites have showed potential for automobile parts in the past several decades, the application has yet to be realized on a mass production scale due to several drawbacks including low production, automation rates, and significant costs. The various manufacturing process (Table 9) and energy consumption to produce composite materials.

Table 9: The energy intensities of manufacturing processes. The manufacturing method involves a different process to produce composite materials. Therefore, the energy intensity varies depending on the production method [149].

Manufacturing Methods	Energy intensity (MJ/kg)	References
Prepreg production	40.0	[162]
Vacuum assisted resin infusion (VARI)	10.2	[162]
Glass fabric manufacturing	2.6	[165]
Resin transfer moulding (RTM)	12.8	[162]
Cold press	11.8	[162]
Wet layup	19.2	[162]

The energy intensities represent energies associated only with processes but not relevant materials. Since the composite materials, in general, involve two or more different materials, processing techniques for composites are quite different from those for metal or polymer processing. After reinforcing fibres and polymer matrices are made, additional processes such as textile manufacturing and prepreg preparation are often required prior to integration of fibres and polymer resins. These processes also need additional energy, although not as much as in the primary processing. In addition to energy, many materials use solvents and additives. In general, during fabrication processes, a significant amount of energy is used to provide heat and pressure necessary for curing.

2.5.1 Polypropylene/Short glass fibres (PP/SGF) composites: Effects of coupling agents on mechanical properties

This study uses the melt compounding method to produce polypropylene (PP)/short glass fibres (SGF) composites as shown in Appendix B, section 1B. PP serves as matrix while SGF serves as reinforcement [42]. Two coupling agents, maleic anhydride grafted polypropylene, (PP-g-MA) and maleic anhydride grafted styrene-ethylene-butylene-styrene block copolymer (SEBS-g-MA) are incorporated in the PP/SGF composites during

the compounding process, in order to improve the interfacial adhesion and create diverse desired properties of the composites [185].

According to the mechanical property evaluations, increasing PP-g-MA as a coupling agent provides the composites with higher tensile, flexural, and impact properties. In contrast, increasing SEBS-g-MA as a coupling agent provides the composites with decreasing tensile and flexural strengths, but also increasing impact strength. The modulus of elasticity in bending, or the flexural modulus (E_{bend}) is calculated in the elastic region. The tensile properties of various PP/SGF composites are compared to those of pure PP/SGF composites (i.e., the control group), as indicated in Appendix B, section 1.B and 2.B. The composites that are incorporated with 8 wt % PP-g-MA have a tensile strength of 79.0 MPa, in comparison to that of the control group (67.6 MPa). The tensile strength of the composites is proportional to the amount of PP-g-MA. In contrast, the composites that are incorporated with 8 wt % of SEBS-g-MA have a lower tensile strength (50.6 MPa) than that of the control group. The tensile strength is inversely proportional to the amount of SEBS-g-MA.

The flexural properties of various PP/SGF composites that are in conjunction with different coupling agents as indicated in Appendix A, section 2. A and 3.A [185]. The incorporation of 8 wt % of PP-g-MA results in a greater flexural strength of the composites (123.4 MPa) in comparison to that of the control group (99.3 MPa) [185]. The flexural strength increases as a result of the increasing PP-g-MA. However, the incorporation of 8 wt % of SEBS-g-MA decreases the flexural strength of the composites to 81.3 MPa. Moreover, the flexural strength of the composites shows a declining trend with increasing SEBS-g-MA content [185].

Short glass fibre in PP/SGF composites is the major material that withstands deformation by an externally asserted force. A PP-g-MA can only improve the interfacial compatibility between PP and SGF, but cannot help resist the deformation. Another factor is that PP-g-MA and PP have similar molecular weights. Therefore, the tensile modulus and flexural modulus of the composites are not correlated with the conjunction of PP-g-MA [186].

The tensile and flexural strengths of PP/SGF composites decrease as a result of the combination of SEBS-g-MA. This coupling agent is an elastomer, which possesses low tensile and flexural Strengths. A greater content of SEBS-g-MA causes the tensile and flexural strengths to decrease. Elastomers improve the toughness of the composites at the cost of sacrificing their rigidity and dimensional stability [187].

2.5.2. Production and mechanical behaviour of glass fibre reinforcement polypropylene (Glass/PP)

The composite laminates (Glass/PP) were prepared in a compression moulding machine using the film stacking technique, by varying the coupler concentration from 5 wt% to 10 wt% and by varying the forming pressure from 4 MPa to 9 MPa. The PP-g-MAH was used as a coupler for the better adhesion of the glass and PP matrix. This is an innovative approach to develop the thermoplastic composite laminates, using the available low cost raw materials, instead of high-end prepreg materials. Very few works have been reported in this area, and it leads to the further study of these materials. Therefore, to access qualitatively the interfacial bonding between the fibre and the matrix, the scanner electron microscope should be used to compare the microstructure [188].

2.5.3 Fabrication of thermoplastic composite laminates

An isostatic polypropylene homo-polymer with a 0.6 mm thick film ($\rho = 0.94 \text{ g/cm}^3$) was used as the polymer matrix, and an E-glass fibre ($\rho = 2.55 \text{ g/cm}^3$) woven fabric (610 gsm) was used as the fibrous reinforcement. In this work, the commercial grade PP-g-MAH pellets ($M_w = 9.1$ by GPC, 8-10 wt. % MAH) were used as the coupler. The properties of the raw materials are given in Table 10. The forming temperature for the fabrication of the thermoplastic composite laminates was set as 190° , which is well above the melting temperature of the polymer matrix [188].

Table 10: Properties of raw materials including mechanical properties and density. To produce composite materials, it's important to know the characteristic of each element such as density, tensile strength [188].

Properties	Tensile Strength(MPA)	Density(g/cm^3)	Tensile modulus(GPa)	Yield strength(MPa)
Polypropylene film(PP film)	39.5	0.94	2	36.5
Glass Fibre woven	1750	2.55	70	----
PP-g-MA	Density: 0.903g/cm^3 Melt Index:120 (190°C/kg calculated) [153]			

The Glass fibre reinforcement thermoplastic (GFRTTP) composite laminates were prepared based on the film stacking technique, using a hot compression moulding machine. The PP film and GF woven fabric were stacked one over the other for 3.5 mm thickness. The stacking sequence has four layers of glass fibre woven fabric and five

layers of PP film. To improve the interfacial bonding between the PP film and glass fibre woven fabric, PP-g-MAH pellets were distributed evenly between them in all the layers with 5wt%, 8wt% and 10wt% concentrations respectively. The stacked alternate layers were placed in between platens of 100 Ton hydraulic press and electrically heated to a temperature of 190°C. During heating, the molten matrix may stick to the contact surface of the heated platens. In order to avoid this, it is advisable to sandwich them between Aluminium (Al) sheets which will enhance the quality of the surface finish of the final thermoplastic composites. The releasing agent was applied to the Al sheets to avoid the sticking. Afterwards, a forming pressure of 4 MPa was applied to the stacked layers for 10 min, by maintaining the forming temperature at 190°C. Then, the material was allowed to cool in the mould to room temperature. The same procedure was repeated for the forming pressures of 7 MPa and 9 MPa to get the next sets of GF RTP composite laminates. The Glass fibre reinforcement thermoplastic composite laminate with a fibre weight fraction of 50% was prepared with 250×250×3.5 mm size for test [188].

2.5.3.1 Mechanical Characterization

After the fabrication of GF RTP composite laminates, test samples were cut to the required sizes, as prescribed in the ASTM standards, for tensile and flexural tests with a diamond cutter. The mechanical properties of the composites were tested by using a 5 Tonnes universal testing machine. During the tests, the load was measured by means of an electronic load cell, and the displacement was measured by a linear variable differential transducer. The experiments were performed with a crosshead speed of 1.5 mm/min [188].

2.5.3.2. Tensile test

The standard followed for the tensile test is ASTM D 638. The tensile testing was carried out at room temperature with the test speed of 1.5 mm/min, to determine the tensile behaviour of the composite specimens [188].

2.5.3.3 Flexural test

The standard followed for the flexural (three-point bending) test is ASTM D-790 (80 x 12.5 x 3.5 mm), and the test was conducted at room temperature to characterize the consolidation quality. Table 11 presents the tensile and flexural strength values of the designed experimental layout [188].

Table 11: Experimental test to determine the mechanical properties of tensile and flexural modulus of composite materials, based on the forming pressure. The analysis shows the variation of mechanical properties when pressure is applied at some level [188].

Experiment runs	Forming pressure(MPa)	Couple concentration (wt. %)	Tensile strength(MPa)	Flexural Strength(MPa)
A	4	5	94	42
B	4	8	109	56
C	4	10	104	51
D	7	5	123	76
E	7	8	128	91
F	7	10	126	69
G	9	5	108	51
H	9	8	113	64
I	9	10	97	51

The tensile and flexural strength values of the designed experimental layout. Based on the tensile and flexural experimental results, the optimal level setting for the better mechanical behaviour is obtained at (Forming pressure) B, E and H (Coupler concentration) ; i.e., Forming pressure is set at 7 MPa and Coupler concentration is set at 8wt% [188].

2.6 Measurements of mechanical property of composite materials.

Natural fibres have been attracting the interest of engineers, researchers, professionals and scientists all over the world. This is due to the method and process used to improve the mechanical and thermal properties of the material. There are many superior properties such as high specific strength, low weight, low cost, fairly good mechanical properties, nonabrasive, eco-friendly and bio-degradable characteristics [189]. Therefore, through the manufacturing process to transform the composite fibre into fabrics, the mechanical properties can be improved considerably. The mechanical properties of composites are a function of shape and the dimensions of the reinforcement [190]. Fibre volume, however, had a significant effect on the final mechanical properties of composites [191]. The elastic modulus E_c of a composite materials can normally be predicted using the standard rule of mixture , which is the simplest and most common, was considered in this research in order to take account of fibre orientation and length effect given in Equation 3 [192]:

Equation 3: The properties of the hybrid system consisting of two components can be predicted by the rule of mixtures.

$$E_c = \eta_l \eta_o V_f E_f + V_m E_m \quad (3)$$

where E_c is the composite young modulus, η_l is the fibre length distribution factor, η_o is the fibre orientation distribution factor, E_f is the elastic modulus of the fibre [44] has estimated a modulus of up to 140 GPa for cellulose fibres), E_m is the elastic modulus of the matrix, V_f is the fibre volume fraction, V_m is the matrix volume fraction (assuming $V_f + V_m = 1$, i.e. no voids or other inclusions) [193].

The Krenchel [194] equation permits calculation of the effectiveness of a mix-aligned fibre reinforcement, as a fibre orientation distribution factor (η_o), using the proportions of fibre at each angle and the fourth power of the cosine of the angle between the fibre and the reference direction. In the manufacturing of composites, volume and weight fractions are usually used. However, in the determination of different properties for the composite materials in terms of the properties of the fibre and the matrix. The following gives relations between volume fractions of materials, resin matrix and weight fractions, as shown in Appendix B, section 3B [195]. The construction of a materials selection relies heavily on a large database that captures and is representative of the variability in typical properties presented in Table 12 [4].

Table 12: Literature survey of typically reported mechanical properties of various natural/synthetic fibre reinforcement thermoplastics (PFRPs), specifically focussing on the effects of matrix type, reinforcement form, manufacturing technique and interface of PLRP mechanical properties [4].

Composite	E-Glass/PP	PP	Flax/PP	E-Glass/PP
Manufacturing technique	Compression moulding	//	Compression moulding	Compression moulding
Reinforcement form	Short fibre 3D-random	//	Long fibre unidirectional	Long fibre unidirectional
Matrix type	Thermoplastic	Thermoplastic	Thermoplastic	Thermoplastic
Tensile modulus(GPa)	6.2	0.1-1.7	26.9	26.5
Specific tensile modulus(GPa/gm ⁻³)	4.8	0.8-1.9	23.6	17.4
Tensile Strength(MPa)	89	20-35	251	700
Specific tensile strength(MPa/gcm ⁻³)	69	22-39	220	461
Reference	[196]	Appendix 2	[197]	[198]

PP = Polypropylene, MAPP = Maleic Anhydride Polypropylene, UP = Unsaturated Polyester, VE = Vinylester

The database is useful to selection and compared some composite materials sure as glass/PP, Flax/PP and the manufacturing technique, matrix type and mechanical properties for some component. And for further research and development to improve the properties of the composite materials.

2.6.1 Estimating weight reduction using young's modulus.

A complete calculation of the potential weight reduction (Equation 4) requires a component-by-component analysis that minimizes weight given the functional requirements, geometry, and material properties of each component. Before making such a large investment, accompany would want a preliminary analysis indicating that the potential benefits from material substitution merit the time and expense. The need for a stiff body drives automotive body panel design [199]. Ashby [66, 200] developed the material index.

Equation 4: Weight of material using Young modulus

$$M = E^{1/3}/\ell \quad (4)$$

Where ℓ is the density and E is the Young's modulus of a material, for evaluating the weight (M) of panels made from different materials with equal stiffness. The following assumptions allow us to approximate the potential weight reduction at equal stiffness:

- Functional, geometric, and material properties are separable;
- performance, as defined by non-stiffness requirements, will be maintained in all components; and
- Only the material thickness will be varied.

Witiket evaluated the potential advantages of some composites (lightweight polymer composites compared against magnesium and steel) in automotive applications. They concluded that the weight reduction does not always lead to better environmental performance [201].

2.7. Stiffness

Stiffness is the next most important property that a composite material specifier usually considers when choosing material. Stiffness is particularly important when determining the correct grade of composite material applications. It is stiffness that enables composite material to be used for a wide range of applications. Without stiffness composites, material would not be able to perform its primary function of providing the composite material content with physical protection. Stiffness (S) itself, is the resistance to bending caused by an externally applied force. This is related to the modulus of elasticity (E) and thickness (t), the expressions are given in Equation 5 [202]:

Equation 5: Stiffness using modulus of elasticity and thickness

$$\text{Stiffness}(S) = \text{Constant} \times E \times t^3 \quad (5)$$

Composite manufacturing moulding process have a significant influence on the final properties of the materials regardless of the part design. Two of the process conditions that have a substantial influence on the behaviour of the composite material are melt temperature and mould temperature [202]. For instance: As the mould temperature increase, room-temperature stiffness of the high-temperature composite also increases. But more significant is the effect of mould temperature on sample stiffness at elevated temperatures [202].

2.8 Conclusion

The research has shown that natural fibre is environmentally friendly and has become increasingly important for industry application. Natural fibre possesses excellent energy management characteristic and lower cost than synthetic material. This concept of bio-based materials has now become of key importance due to the need to preserve our environment. Bio fibres like flax, sisal, coir, hemp, palm oil are now finding applications in a wide range of industries. The field of bio comp-fibre research has experienced an explosion of interest, particularly with regard to its comparable properties to glass fibres within composites materials. The main area of increasing usage of these composites materials is the automotive industry, predominantly in interior applications. The process of composite material developed in recent year has consisted of superposing layers of materials, for example the production of flax matt and hemp into sheets for the Henry Ford car, the production of glass sheet and polypropylene film for component parts. Therefore, the transformation of flax fibre, glass fibre and polypropylene into sheet, matt and film materials may increase the thickness and irregularity of the finish surface when combining both flax sheet and hemp sheet or glass/PP into composite materials. The production of fibres, such as flax, PLA, MAPP and hemp, show other advantages for combining to form two materials in one, into tape fabric. Then, the composite materials tape will be used with matrix resin to have a constant thickness and less weight. This method improves the overall mechanical and thermal properties of the natural composite tape.

The life cycle assessment is used to evaluate the production process of raw material extraction through processing, manufacturing, distribution and disposal. A Simapro software tool is used to assess the energy for the production of natural fibre compared to some synthetic fibre. Through this process of life cycle assessment, we determine the system boundary energy use and environmental impact. Most recent research has not used LCA on the development and production of the bio comp fibre and composite material. The development of composite materials show us different combinations of composite materials and hybrids. Therefore, research on the environmental impact was not evaluated before any production process. They were interesting to focus on the application of LCA using Simapro eight and ecoinvent through the manufacturing process of the composite materials.

The production of the composite material varies depending on different processes with matrix resin such as compression moulding, prepregging and vacuum infusion. The literature show that the LCA of the environmental impact was not evaluated during the moulding process, therefore, it is critical to estimate the energy consumption and

environmental impact during this process, in our workshop, to reduce the greenhouse gas emission in the near future .The manufacturing process of composites materials has a significant impact on mechanical properties. It is crucial to estimate the mechanical properties of the composite material produced. The considerable advantages of using composite material are less than thirty percent weight reduction, better than mechanical and thermal properties.

Chapter 3 Materials and methodology

The materials, methodology and resources used commercial device software and Simapro LCA to develop the life cycle assessment gate to gate, were applied directly on the transformation and production of the composite material. The system boundary was defined, to show the input and output of the manufacturing process, then examined the functional unit attributed to the primary data. The results of the simulation are produced and interpreted through process tree and environmental impact. The mechanical properties of those materials obtained and were discussed in the result section for further improvement.

3.1 Materials

In this study, four types of fibres materials was used, namely flax, Polylactic acid (PLA), Maleic anhydride polypropylene(MAPP) and glass fibre. The tape machine and the triaxial machine were involved in the transformation of the fibre into composite tape and fabric. The compression moulding machine was used for the moulding of the composite materials and resin matrix to form a part. The life cycle evaluation of flax/PLA tape and triaxial glass fibre, were based on studies of a tape machine in Tilsatec and weaving machine glass /carbon fibre in Formax and the compression moulding process in Netcomposite. Tilsatec used purchased flax and PLA fibre from Europe (Belgium and France) for the production of composite flax/PLA tape. While Formax used purchased glass/carbon fibre tows and transformed them into triaxial glass fibre fabric. The manufacturing process for the production of triaxial glass fibre fabrics used glass tow and constant thickness.

On this method, the machine is connected to a commercial device and software to monitor the energy consumption in real-time during the manufacturing process. The experiment method was divided into three groups. The machine tape, the triaxial machine and compression moulding machine used the same tool for energy consumption during the manufacturing process and was safely monitored before and at the end of production. The data was collected and materials were inputted using simapro 8 LCA software to produce the process tree and environmental impact. The composite tape is tested through mechanical properties for further comparison with other materials. The experimental method was provided to extract the primary data, presented secondary data collection and also through calculations. Figure 5 presented the overall connection between machine and data collection.

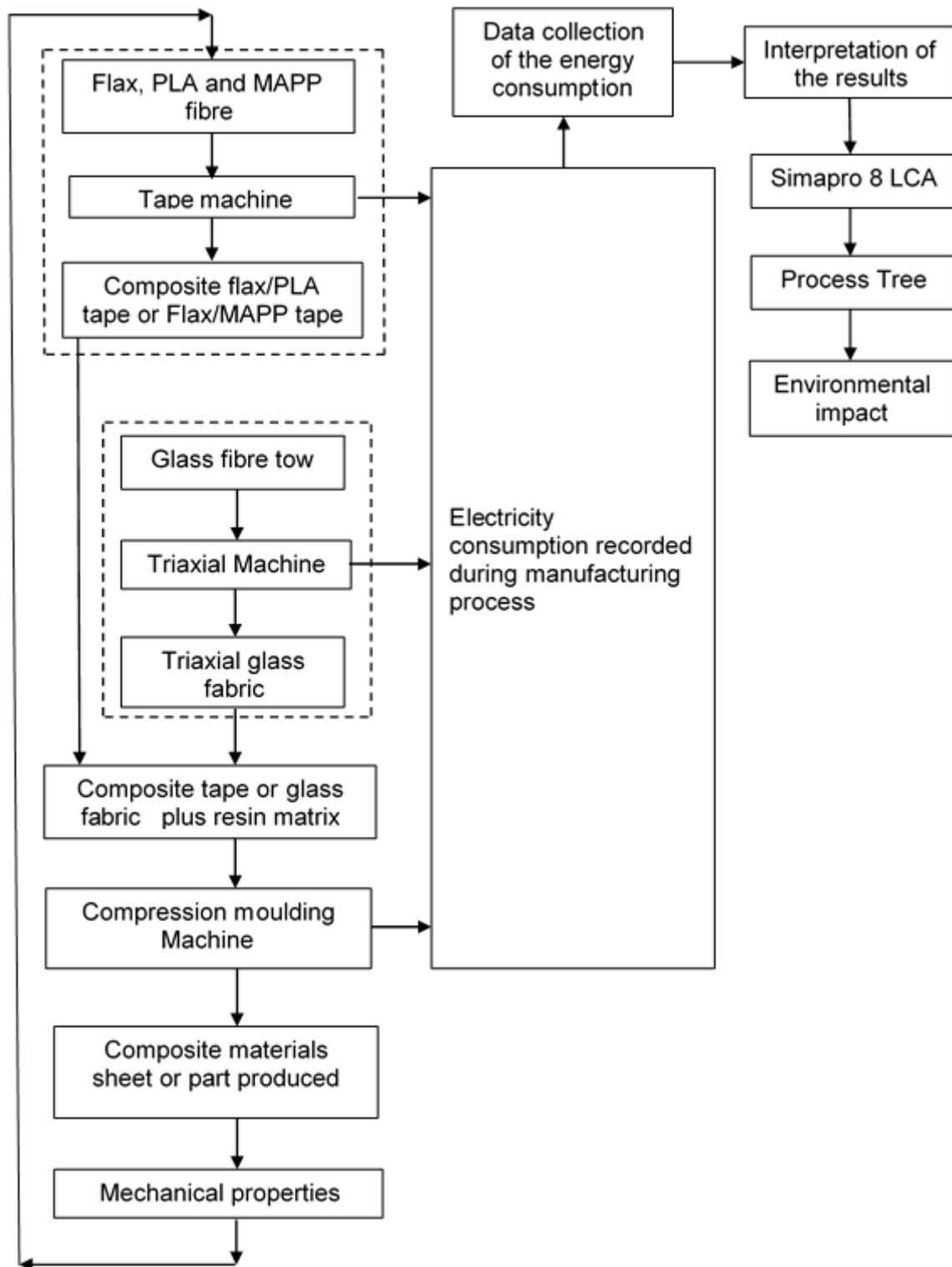


Figure 5: The figure shows that each manufacturing process is connected to the energy consumption device. The machine transmits the electricity usage, using commercial device software eferty, to collect the energy consumption during manufacturing for each method. The data is collected and inputted on the Simapro 8 LCA software to simulate the process tree and environmental impact.

The material process is connected to the compression moulding machine. The moulding machine used the composite tape or fabric with resin matrix for the production of the component. Then, the mechanical properties determine the characteristics of the composite tape part or fabric plate. Different ratios of flax/PLA and flax/MAPP are combined and tested to improve the mechanical properties through manufacturing. The middle and right side in figure 5 represent the data collection and interpretation of the electricity used for the transformation and fabrication of the composite materials.

3.2. System boundary LCA gate to gate fibre into fabric

According to the ISO 14040, ISO 14041, and ISO/TR 14049 standards [203], a system boundary is determined by an iterative process in which an initial system boundary is chosen [204]. Then further refinements are made by including new unit processes that are shown to be significant by sensitivity analysis [204]. An elementary flow is defined by material or energy entering the system being studied, which has been drawn from the environment [205]. This has previously not been transformed by humans, the materials can be discarded into the environment. The resource, activity and emissions of an LCA gate to gate is limited in a single process. Therefore, the three phases of life, are seen as a self-contained unit, with notional “gates” through which inputs pass, and outputs emerge. Figure 6 illustrates the input and output system boundary to seek maximum energy used. This action by one phase may have the result of raising resource consumption such as electricity and emissions for the manufacturing process, which are due to the production of the composite material part on special machinery for a single output.

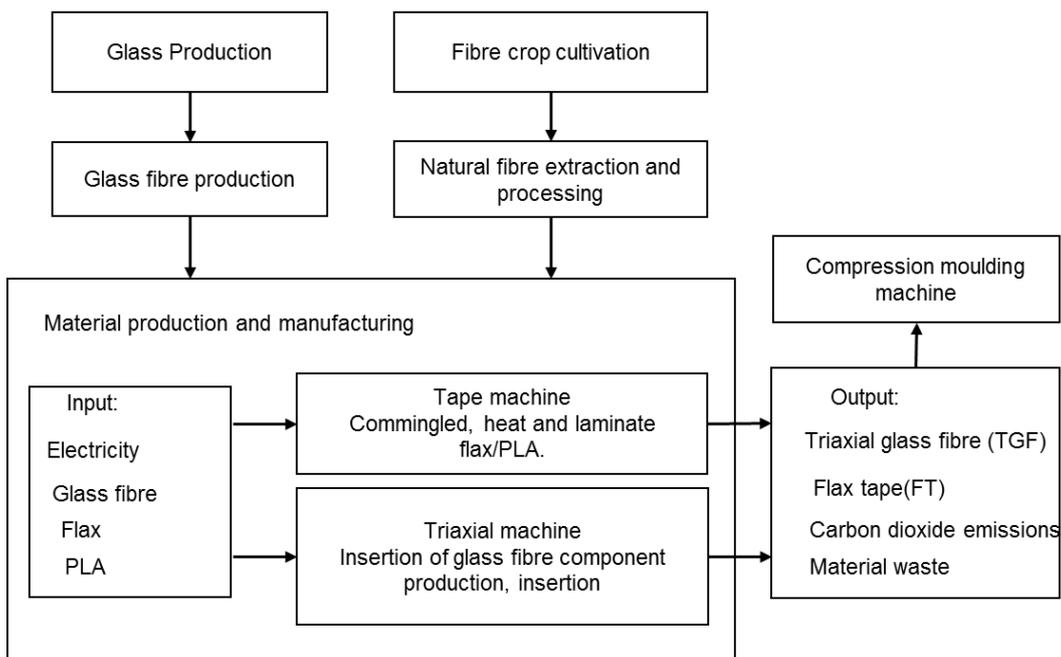


Figure 6: System boundary of the material transformation gate to gate for the inputs and outputs of glass fibre reinforced plastic (GFRP) and flax/PLA tape and compression moulding machine.

This graph focuses on the production process of flax, PLA, MAPP and glass fibre in to composite materials fabric and parts. The system boundary focuses on a specific process to show the input and output on the manufacturing, by showing the material use, at each step of the transformation of the product. This will help to apply LCA to determine the energy consumption and carbon dioxide emissions on the system boundary. The input is connected to electricity and materials (flax, PLA and glass fibre), the Tape machine and triaxial machine to transform the materials into tape or fabric that represent the output. All this connection form a system boundary for the production process.

3.3. Process to transform flax/PLA tape and triaxial glass fabric into composite materials.

The composite flax/PLA and the triaxial fabric was used with matrix resin to form a new composite material. Different processes and methods were involved in achieving the end components like prepreg processes, cures, and compression mouldings. The natural fibre was used to produce composite material laminates for applications in the industry [206]. A semi-consolidated sheet prepreg was developed from fully aligned natural fibres flax, polylactic acid and maleic anhydride polypropylene in the form of composite flax/PLA tape. The focus was on processes that can be fully integrated with the spreading and orientation technologies and improved fibre-matrix adhesion. For commingled composites, the blending of natural fibres and polymer fibres was studied and defined. The mechanical properties have a significant impact on the selection of natural fibre Appendix A, section 4.A [223-225],[42].

3.3.1 Process to produce flax/polylactic acid (flax/PLA) and flax/MAPP in to composite tape.

The combination of several types of fibres into a single material has led to the development of hybrid bio composites fibre. The properties of the hybrid system consisting of two components can be predicted by the rule of mixture. When developing a range of laminate mixed composite material; some theoretical calculation has to be established to define the percentage of each composite material. To develop and find the percentage of each flax, PLA and MAPP fibre to blend and form a composite fabric before processing into composite flax/PLA or flax/MAPP tape to find the best combination based on the

mixture and mechanical properties after the test. Therefore, the rule of the mixture of flax and PLA is governed by the weight (W_c) of the composite material in Equation 6.

Equation 6: weight of the composite tape materials

$$W_{\text{flax}} + W_{\text{PLA}} = W_c \quad (6)$$

Where W_c is the total weight of the composite to produce, W_{flax} is the weight of flax and W_{PLA} is the weight of PLA. This method is introduced to calculate the percentage of flax and PLA fibre needed to be blended to form a composite flax/PLA tape. Assuming that the composite material consists of two different types of fibres (flax and PLA), the weight of the composite is equal to the sum of the fibres. Therefore, we find the weight of each type of fibre. The weight of the composite material flax and PLA can be determined using Equation 6.

The focus was on the development of an integrated approach that combines the fibre spreading and arrangement technology into a single continuous process that can be readily up-scaled for commercial production. Depending on the mechanical properties to improve, we can increase or reduce the fibre percentage of one of them. For example, to produce 80 kg of fibre with 60% flax and 40% PLA, we will need 48 kg of flax and 32 kg PLA mixed to form a composite flax/PLA tape. Table 13 predicts a random volume ratio was selected for the blending process.

Table 13: Selection of the different ranges of blends based on the composite tape materials produced. This method is to control the percentage of flax or PLA fibre to be mixed together to form a composite tape material.

Uni-directional tape	Wettability (%)	Selected blends
Scenario 1: Flax/PLA 170 gsm 170 mm width medium to high consolidation	10% PLA	40/60
		50/50
		60/40
Scenario 2: Flax/MAPP 170 gsm 170 mm width very low consolidation	10% MAPP	40/60
		50/50
		60/40

The first stage of the product lifecycle is material production, for natural fibre, which involves processing the blend selected into flax/PLA or flax/MAPP tapes by lamination using a tape machine. The composite flax/PLA and Flax/MAPP tapes are produced using the same process parameters. The production of the composite tape is 170 mm width at 170 grams per square meter.

The fibre followed a conveyor bench before going through a blending process. Figure 7 shows how materials flax/PLA (polylactic acid and flax fibre) are passed into the blending inputs to be mixed and aligned. Moreover, they move through a hot cylindrical wheel machine, laminated at elevated temperature (170 degrees) and are transformed into a composite material called flax tape. The speed, set at 4m/min, and temperature are monitored to obtain a high-quality composite flax/PLA tape. During the single process of blending and laminate, electricity was used, and CO₂ emissions were produced.



Figure 7: Process for transforming flax and Polylactic Acid (flax &PLA) into or flax/MAPP composite material flax tape. The composite fibre passed through a blending part of the machine and later through a hot laminate section of the machine set at 170°C to form a composite tape fabric. The machine tape used purchase electricity and the heat was not take into consideration.

3.3.2. Process to produce triaxial glass fibre

Formax is a leading manufacturing company transforming roving/yarn into fabrics using the triaxial machine presented in Figure 8. The energy consumption was evaluated during the manufacturing process of glass fibre. The average electricity use depends on the machine set up and speeds at 1m/ min. The method to transform glass fibre roving into the fabric is the same process using the same machine to produce carbon fibre fabric. The glass roving is passed along the rolling table inserted, stitched and woven at - 45°,90°,45° and batched.

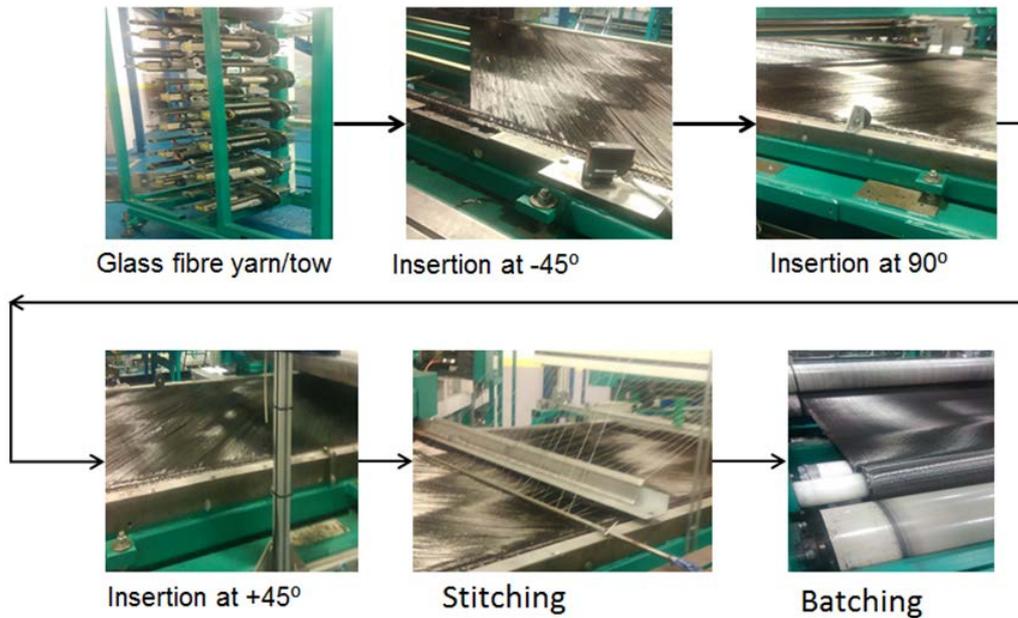


Figure 8: Manufacturing process of multi-axial glass fibre into fabric. The fibre tow is held on the rail before to transfer into lines on the triaxial table machine arranged on the top of each other at different angles and stitching to form a composite glass fabric.

This triaxial machine shows the manufacturing process of composite tri-axial glass fabric and each step of the production. The production of triaxial glass fibre involves loading glass fibre tow on the rail of the machine that had formed layers following different angles to produce a multi-axial layer glass fabric. The machine used purchase electricity for the production.

3.4 Compression moulding

The compression moulding machine was used to press and mould composite material with a heating and cooling system. The compression moulding parts applied pressure on the usually preheated moulding materials to force it into contact with the mould; these are, for example, the upper movable mould part, the lower fixed mould part and the ejector pin. A cooling machine system is connected to the machine parts of the mould for rapid cooling down on the top and lower part of the mould. The machine was used to produce thermosetting prepreg, fibre-reinforcement thermoplastics. When processing the engine, the composite material is loaded cold, although the tool itself may be preheated. The impregnation process with compression moulding consists of spray using resin and dry the composite materials.

The process can be made by hand lay-up or using a conventional prepreg machine. For mass production, the material passes through a resin basin and between two calendar rollers, to reduce the excess of resin by lamination and then through a heater system to be dried and stored. The process uses a conventional machine such as air compressor, heat for an air compressor and vacuum pump. The composite material prepreg is dried under vacuum at 100° C during 20 min, to drive off the water; therefore, the energy consumption of the process can be estimated. On this case, the dry flax/PLA tape of 250 mm x 250 mm was impregnated manually. Then the composite flax tape layers were dried using an air compressor. The moulding cycle time for the compression moulding process is calculated using Equation 2 Chapter 2. Figure 9 shows an overview of the compression moulding machine and the process to set up the moulding operation.

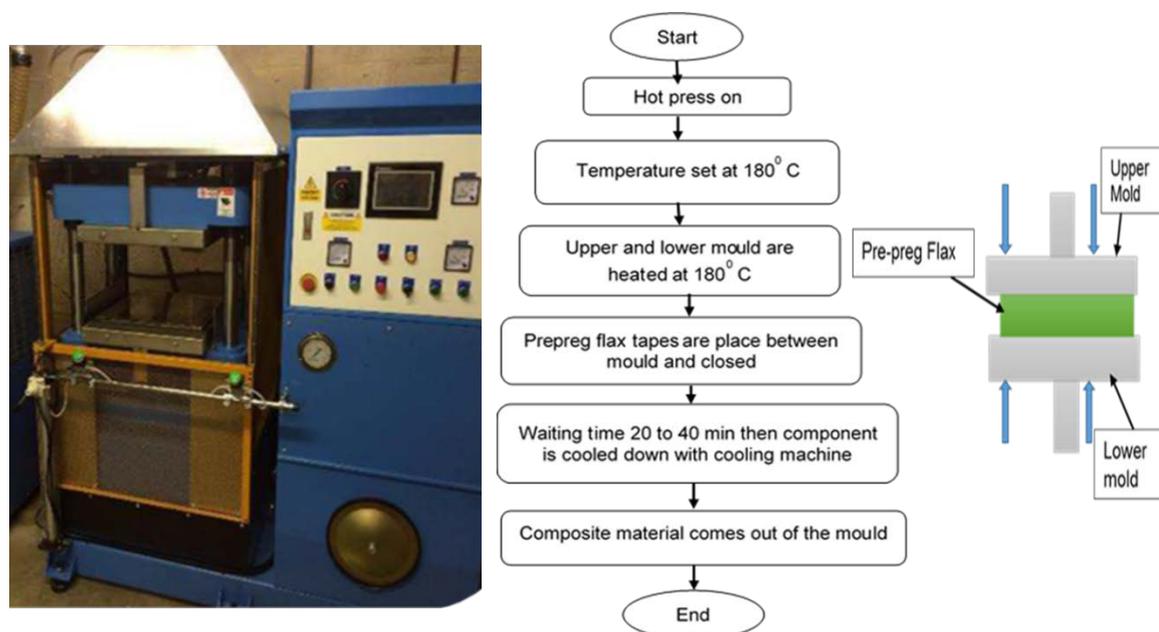


Figure 9: Compression moulding with a cooling machine system in Netcomposite. This machine, set with a cooling system that allows the composite material to cool down efficiently before opening the mould. A flow-chart to the left shows the moulding process to produce composite flax/PLA tape layers set at 180° c. Moulding time, including heating and cooling the upper and lower mould, is approximately 20 to 40 min. The schema of the right indicates the compression moulding process for the natural composite material prepreg flax.

The Composite tape and fabric with different layers were manufactured using compression moulding methods. The composite flax/PLA tape layers have a thickness of approximately 1 mm impregnated and dried in an oven to reduce the influence of moisture, later placed in the fridge for 24 hours before moulding. The composite tape plate can be

manufactured by film stacking method in a temperature-controlled hydraulic press by heating and compressing and later cooling. In this stacking method, pre-dried layers randomly oriented, non-woven flax/PLA and flax/MAPP with the bio-furan resin to obtain a good fibre impregnation.

3.4.1 Process to produce composite tape plate

To manufacture a composite material impregnated using compression moulding process, eight layers of sheet flax/PLA tape has been used and placed on the mould. All composite plates were heated for 20 minutes at a temperature of 180 degree and were put under pressure of approximately 8.0 MPa. The pressure was increased in steps to avoid the presence of bubbles and voids .To observe the effect of cooling temperatures the moulds were cooled at two different temperatures 20 degree and 60 degree. The time and heat of moulds were selected, depending on the number of layers and the total thickness of the composite materials. Some dry area appears on the final moulding process due to the impregnation process. A range (Table 14) of composite flax/PLA and flax/MAPP tape that was mould to form a composite materials.

Table 14: Specification on the laminate thermoplastic panel before moulding and after the moulding process. The composite materials showed a considerable weight loss after the moulding technique.

Panel	Resin wettability %		Fibre volume %	Weight loss(g)
	Before pressing	After pressing		
Flax/PLA(Thickness 2.5 mm)				
40/60	53.77	45.07	51.88	8.7
50/50	51.66	46.18	50.76	5.48
60/40	50.68	45.81	51.81	4.87
Flax/MAPP (Thickness 2.8 mm)				
40/60	49.30	45.76	51.17	3.54
50/50	46.40	45.11	51.83	1.29
60/40	47.41	45.20	51.74	2.21

The different ratios of composite flax/PLA and flax/MAPP tape layer before and after pressing to evaluate the weight loss. The higher weight loss is estimated at 8.7 g and the lower weight loss is 1.29 g. The laminate plate was processed by using vacuum infusion and Scott Badder Crestapol 1250 L resin, with a calculation fibre volume fraction of 51.88 % on a press mould presented in Figure 10.

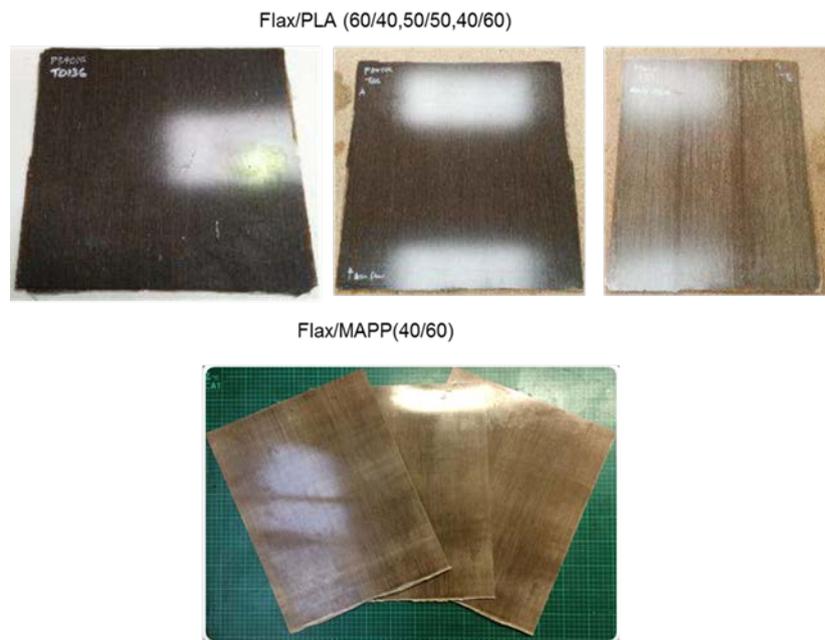


Figure 10: Laminates 8 plies unit directional, 130 x 390 mm, [0/90] direction. Different samples of composite flax/PLA and flax/MAPP tape was produced using the compression moulding process. The percentage of flax has a great influence on the composite materials, shown by the colour.

Laminates of flax/PLA and flax/MAPP, with the compression moulding process, show a suitable surface aesthetic finish of the composite materials. Energy consumption and mechanical properties were estimated to find the appropriate combination ratio. The thickness of the plate is 2.5 mm for flax/PLA and 2.8 mm for flax/MAPP. The best ratio of composite material will depend on the mechanical properties of the composite materials; for example, a high volume fraction of fibre will increase the tensile strength.

3.5. Data collection methods

The measurement for LCA gate-to-gate was developed to collect data and analyse. Some primary tools and devices were used, such as E2 link classic software and Simapro eight. The model e2 classic receives the electricity transmission time at 6, 12, 18 seconds, at a frequency 433.5 MHz with a sensor voltage range 110-600v, measuring current to 50mA-90A which are interconnected and suitable for on-site data collection. They allowed recording direct data of the energy consumption and CO₂ emissions during the production of the composite materials. This measurement required skill from the operator and time to fix the device on the machine during the manufacturing process. The data used estimated the cost, CO₂ emissions and embody energy used, to produce a natural composite material and then compare this to other synthetic materials. The treatment of electricity was a crucial point in each material intensity analysis as in each life cycle analysis. Thus, as power used in nearly all production processes, results have rarely influenced the choice of the approach. The measurement was based on the machine and method used, to produce new composite material and to use Simapro 8 software to analyse the whole process. Inventory analysis involves the compilation and qualification of the inputs and outputs for each gate of the process, for a given product system throughout its life cycle. Figure 11 presented a schematic design method set up to produce composite flax/PLA tape, prepreg and moulding processing, to determine the energy consumption followed by the carbon dioxide emissions.

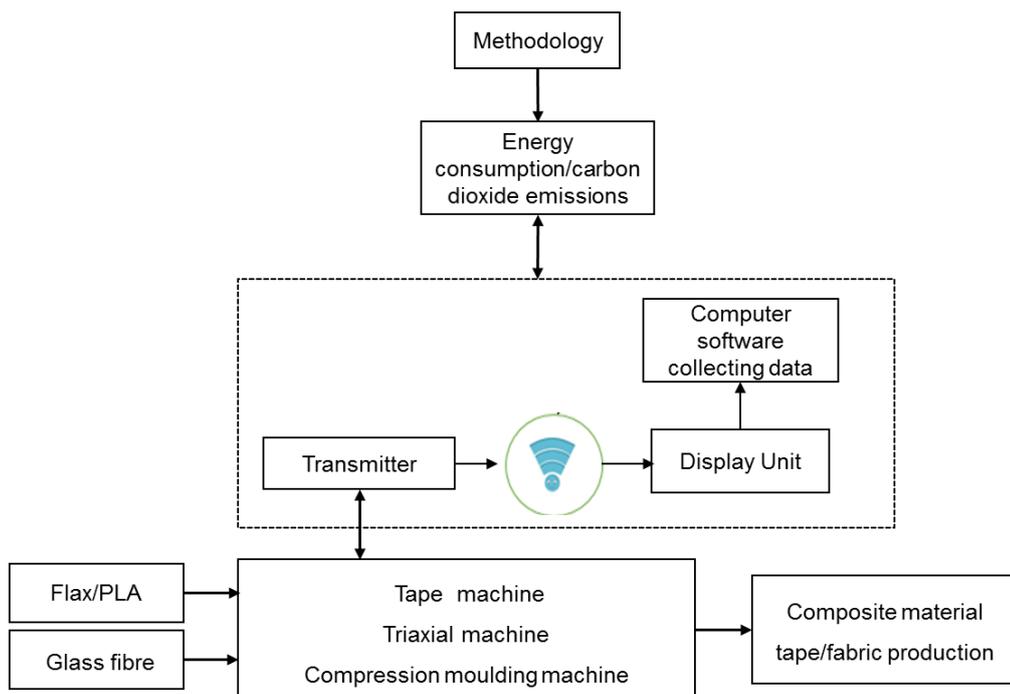


Figure 11: The schema shows a brief methodology of the material description of the connection use and overall procedure. The method connected the device and recorded the primary data (electricity and carbon dioxide emissions). This process allowsecoinvent software to connect to the machine during manufacturing and transfers the energy consumption in seconds, via wireless to a computer to record the electricity used.

The energy consumption was recorded for each manufacturing process for flax/PLA tape and triaxial glass fibre, impregnation, drying under vacuum and moulding process on a specific machine. The device and software were connected at the beginning of each process, to collect the primary data and, to estimate the change in electricity used and carbon dioxide emissions as a function improvement on the mechanical properties through the moulding method. The characteristic of the composite material was evaluated through mechanical properties and could be improved.

3.5.1 Method to collect the energy consumption for a single process

The measurements consist of using a domestic electricity usage monitor to compile gate-to-gate (GtG) LCA data for the project. A current sensor is clipped on to the supply cables. A lead from the sensor is plugged into the energy transmitter, which then wirelessly sends real-time data to the energy monitor. The monitor receives the data and displays the demand in kilowatts of energy consumed at any given time. Therefore, the data can be exported to the efergy elink 2.0 software and can be analysed and extracted on to Excel for further investigation presented in Figure 12. The vertical line represents the electricity use for a single process, starts to rise with time per hour by showing the electricity use during a period. The carbon dioxide emission is deducted from the electricity used per hour. The orange line Colum represents the higher pic point and the green line are the started and end pic point for the energy consumption.

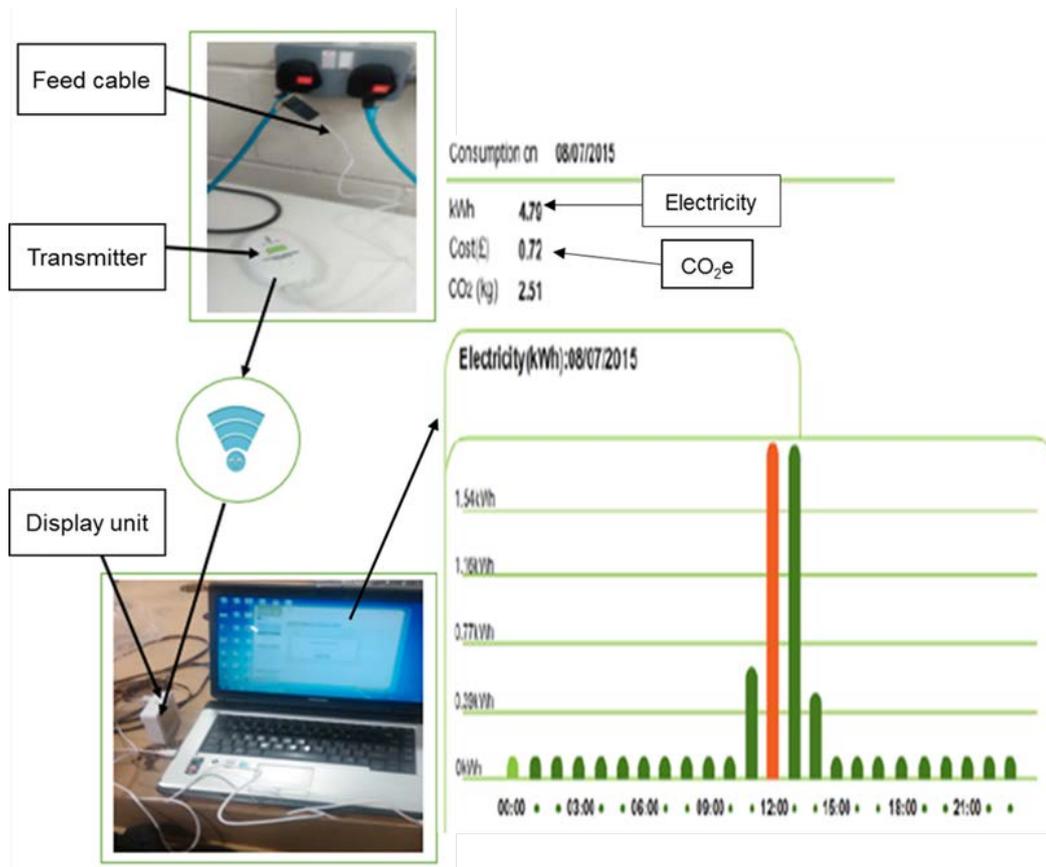


Figure 12: The computer system is connected to a device, a call display unit, to receive the data. The display unit receives data via wireless to the transmitter. The transmitter is connected to the electrical supply machine source to measure energy consumption. E2link software energy consumption presents how energy consumption increased and decreased during manufacturing on the computer screen. The orange Colum indicated the higher peak point, and the green bar indicates the start and end of the energy intensity at this time.

Any power used during the process will pass through the sensor cable. The clip-on sensor acts as a current sensor, relaying the amount of current drawn on to the machine using the transmitter. From there, it is sent wirelessly to the monitor display unit, which shows how much power is consumed. The monitor shows instant power (kW), estimated electricity per hour and carbon per hour (kg.CO₂/hour). The capacities of the devices, to collect data, depends on the specification and technical information. The distance range of the sensor for transmission is less than 70 metres; the sensor voltage range is around 600 v. If we have a three-phase supply, then additional sensors may be required. These can plug into other sockets on the base of the transmitter. The monitor is attached to the computer software elink with the correct conversion factor. During production, the

evaluation of the carbon dioxide emissions with energy consumption is collected through the monitor, displayed on the screen in second. The graph of direct electricity consumption and carbon dioxide emissions is analysed through Excel. This data will be used on SimaPro LCA to reproduce the manufacturing process.

3.5.2 Methodology to use SimaPro LCA wizard

The LCA Wizard is focused on a specific product. In practice this means wizard is used to deal with a similar topic or issue. We used wizard on LCA to input our data and create our own manufacturing process to simulate the environmental impact. Through this method, we will extract the process tree and the environmental impact.

3.5.2.1 SimaPro LCA wizard

The purpose of the LCA wizard is to show in Figure 13, how to use the feature to the model the life cycle of a product in Simapro, using the various products stage in Simapro. The model will be an example of the production of CD-ROM by opening the project 'Introduction to SimaPro'. We started the LCA wizard and defined one assembly and associated life cycle with the following materials: Polyvinylchloride, Aluminium, and Polypropylene [207].

Municipal waste handling has a relatively low contribution. The waste scenario splits the waste stream in a part that is landfilled and a component that is incinerated. SimaPro has individual waste treatment records to model the incineration and landfill. SimaPro automatically analyses the material contained in the waste flows and connects them to the proper waste treatment record (for this, each element has a label that describes the waste type) [207].

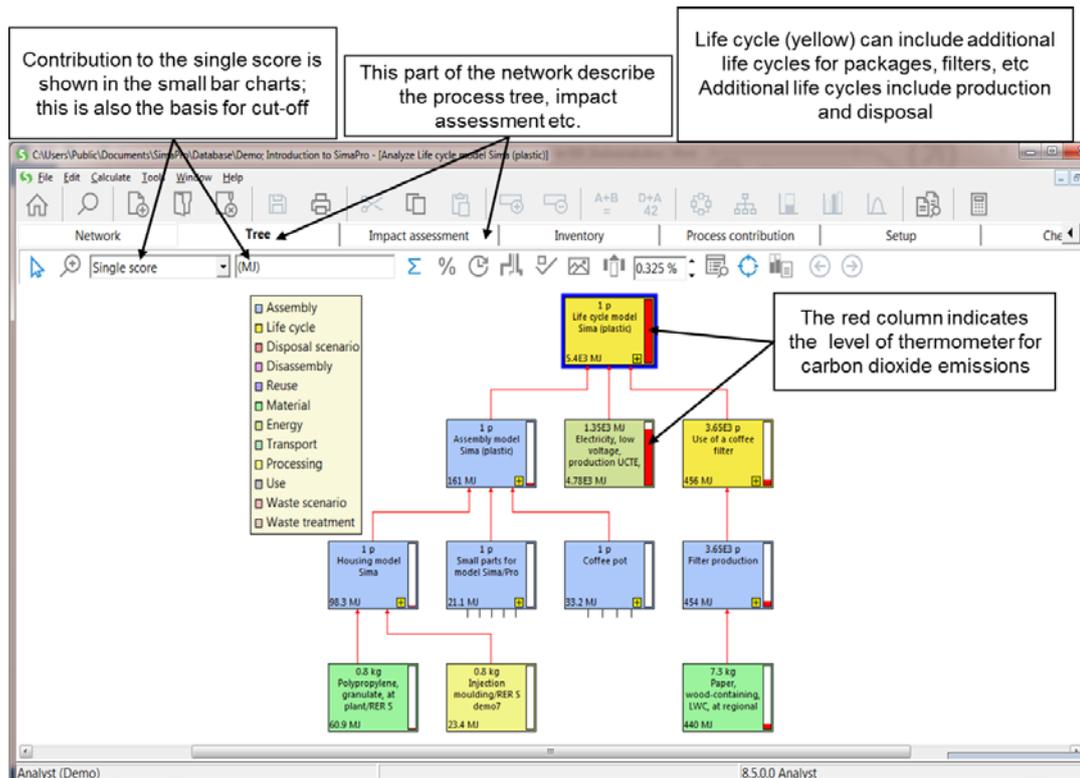


Figure 13: Simapro 8 software, an example of a LCA process tree CD-ROM production without recycling. The Simapro software reproduced the manufacturing of the CD-ROM and showed the area where the carbon dioxide is higher in the red column. This process tree was created with wizard on LCA for the CD-ROM [115].

Working with product systems is relatively simple, but it has some limitations. If we want to understand the details of the system we have built, we go to the product stages section [208]. Under assembly, with the subcategory of others, we will find the four assemblies defined in the Wizard [208]. We can open these and inspect or edit them. The system includes the life cycles, assembly and disassembly stages under others. Note that if we make changes in these product stages, these changes will not be made in the product systems. SimaPro LCA software was used to model and report with intuition data collection and results from analytics [208]. Therefore they will help to save money, reduce risk, communicate product benefits and increase revenue. Its' use on those examples, to simulate and assess every raw material and process in every phase from extraction to end-of-life across the supply chain is shown [208].

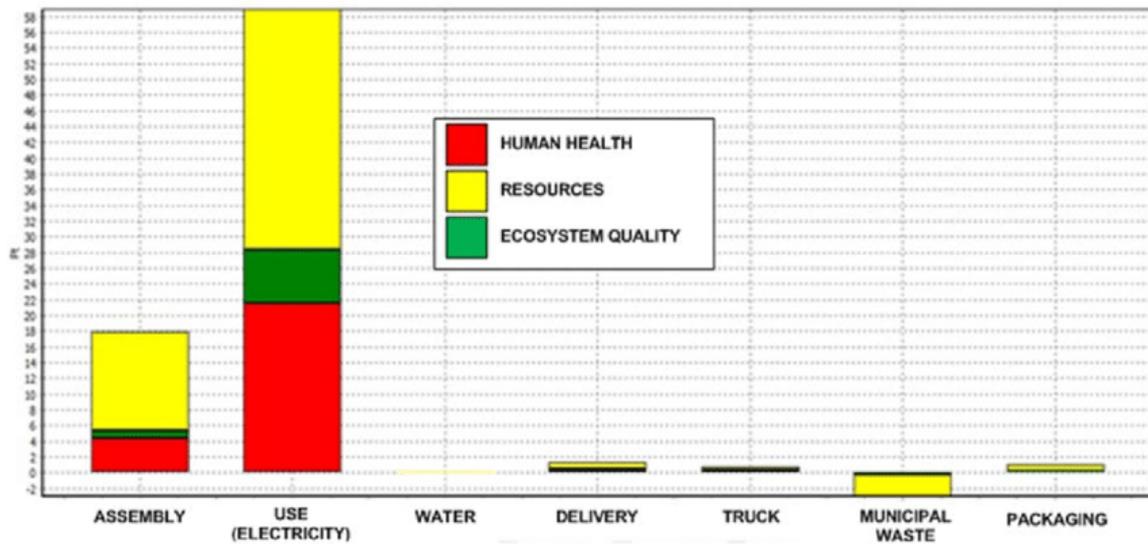


Figure 14: Example - showing a LCA ECO indicator 99. The environmental impact of the product during assemble, use, delivery, waste on the human health, resources and ecosystem quality [208].

The selection of the icon such as the network, tree, impact assessment method to analyse the whole process and identify the area which uses more electricity and produces additional carbon dioxide emissions. Moreover, the impact assessment is used to show the influence of the production on human health and the environment. The system prefers to predict the manufacturing process of the system if one uses a single score presentation or weighting. This example is followed by the environmental impact or network connection for short term or long term production. Contribution analysis shows all processes tree (Figure 14) that contribute to the ecological impact.

3.5.3 Method to calculate the electricity and carbon dioxide emissions

To model the product system, LCA uses a functional unit. ISO 14040, which defines the functional unit as “quantified performance of a product system for use as a reference cell [209]. The functional unit is the principal basis that enables alternative goods, or services, to be compared and analysed and is not usually just a quantity of material. Practitioners may compare, for example, alternative types of packaging by 1 m³ of packed and delivered product and the service that the product provides. The amount of packaging material required, termed the reference flow, can vary depending on the packaging option selected, i.e. paper, plastic, metal, composite [210]. For the production of composite materials, using natural and synthetic raw material, the process will depend on the method used during manufacturing. Therefore, the functional unit for the production of natural fibre composite material flax, polylactic acid and synthetic material carbon fibre was estimated in metre per minute (m/minute) during the manufacturing process. All input and output data is allocated to the functional unit of the material produced in millimetre (mm), based on electricity consumption in kW/h and CO₂ emissions (kgCO₂ per kWh electricity). The electricity used in kWh or Mega joule (1 kWh=3.6 MJ or 1 MJ=0.2778 kWh) is converted into kg of carbon dioxide by using the conversion factor. If a 1000 kWh unit of electricity is consumed, we can calculate the CO₂ emissions by using the conversion factor on Appendix C section 1C and 2C [211, 212]. The conversion factors (CF) for the energy source is 0.523 kgCO₂/kWh [212] and for the impact assessment factor (IAF) of the carbon dioxide emissions (CO₂e) is 1 Appendix C section 1C and 2C [212]. The primary data is obtained by using the standard method software and formula applied to a specific process. The electricity and carbon dioxide emissions are calculated from the activity data supplied by the partner. Based on the power of the motor and the manufacturing time for a specific machinery. The greenhouse gas emissions is obtained by multiply the emissions factor and the carbon dioxide emissions.

3.5.3.1 Theory approach to calculate the electricity

Theoretically, there is some familiar assumption base on Ohm's law using electrical power (P, in watts) [213] indicated on the motor power. Therefore, electricity is power multiplied by time. But it's not always informal to calculate when there are more than two motors on the similar machine such as a triaxial machine. Moreover, further process and method are developed for each production process and more details produced. The energy consumption will depends on the time that the machine is operated.

The energy E in kilowatt-hours (kWh) per day in Equation 7 is equal to the power (P) in watts (w) multiplied by the number of usage hours per day (t) divided by 1000 watts per kilowatt [214].

Equation 7: Energy consumption E (kWh/day).

$$E \left(\frac{\text{kWh}}{\text{day}} \right) = P(w) \times \frac{t \left(\frac{\text{h}}{\text{day}} \right)}{1000 \left(\frac{\text{W}}{\text{kW}} \right)} \quad (7)$$

Where E represents the energy in kWh/day, the power P in watts and the time is in hours (Hrs).

For example: An electric motor with 1.1 kW single phase with 230V, single phase, 50 Hz and full load current (FLC) 7.0A.

$$E(\text{kWh}) = (230 \times 7) \times \frac{8}{1000 \left(\frac{\text{W}}{\text{kW}} \right)}$$

$$\text{Energy (E)} = 12.88 \text{ kWh/day}$$

The energy represented for 8 hours production with an average of 12.88 kWh/day. There is a simple step to obtain the electricity use and hence to calculate the carbon dioxide emissions. The process generated a regular data base on the specification on the machine for a long run or short run time.

3.5.3.2 Carbon dioxide emissions and greenhouse gas emissions (GHG)

The quantitative measurement of activity from a product's life cycle is found, when multiplying the electricity used by the appropriate conversion factor, determining the CO₂ emissions arising from a process [215]. For example, a primary activity data includes: the amount of energy used, material produced, service provided and sources which are typically preferable to subsequent lines of evidence. The data will reflect the particular nature/efficiency of the process and the CO₂ emissions produced. As a result, the primary activity data does not include conversion factors.

We can use the conversion factor (Equation 9) to calculate the carbon dioxide emission from electricity use. There are no standard methods to estimate the energy consumption of machinery during the production process, but standard and simple conventional factor tools have been used to quantify the carbon dioxide emissions of machinery during production.

During the manufacturing process of materials and composites materials, some materials used more energy than others, therefore producing more carbon dioxide emissions according to the British standard of LCA. According to Jan, It is necessary to evaluate the environmental impact of the whole process to design and produce new material that can be more suitable for industry [216]. The conversion factor is used to convert the electricity consumption to obtain the carbon dioxide emissions produced. We can calculate the CO_{2e} by using equation 8.

Equation 8: CO_{2e} using energy consumption (E) and conversion factor (CF).

$$E \left(\frac{kWh}{Day} \right) \times CF (kg CO_2 / kWh) = kg CO_{2e} \quad (8)$$

So, for 1000 kWh × 0.523kg = 523kgCO₂ will be produced.

Another parameter, such as heat and waste of material, has not been considered during the production process. The carbon dioxide emissions is deducted from the energy consumption.

The global warming potential (GWP) or GHG was developed to allow comparisons of the global warming impacts of different gases Appendix C, section 1C and 2C. Specifically, it is a measure of the discharges from 1 tonne of carbon dioxide (CO_{2e}). The impact contribution of a product is found by multiplying the number of carbon dioxide emissions

by the impact assessment factor [215]. To calculate the greenhouse gas emissions (GHG) or GWP, collect or estimate activity data for the specific machinery, for example amount of electricity used. Then multiply this activity data by the relevant (emission) conversion factor. This gives an estimate of the GHG emissions for that activity. $\text{GHG emissions} = \text{activity data} \times \text{emission conversion factor}$ [217]. Direct global warming potential is the sum of gas multiply by the impact assessment factor in Appendix C, section 1C and 2C, expressed in Equation 9 [100, 217]:

Equation 9: Direct global warming potential (GWP) [217].

$$\text{GWP} = \sum \text{CO}_2 \times \text{IAF} \quad (9)$$

The inventory analysis provides emissions data in terms of kg/functional unit, for example, 10 kg carbon dioxide, 5 kg methane [100]. GHG emissions are converted into equivalent amounts of carbon dioxide (kg eq. CO_2) by means of Global Warming Potentials (GWP)

10 kg carbon dioxide = $10 \times 1(\text{GWP}) = 10 \text{ kg eq. CO}_2$

Quantity of CO_2 released = 10 kg (CO_2 GWP factor value is 1)

Quantity of methane released = 5 kg (methane GWP factor value is 23)

Therefore, $\text{CO}_2 \text{ GWP} = 10 \text{ kg} \times 1 = 10 \text{ kg CO}_2 \text{ eq.}$

$\text{CO}_2 \text{ methane} = 5 \text{ kg} \times 23 = 115 \text{ kg CO}_2 \text{ eq.}$

Total GW impact = $10 + 115 = 125 \text{ kg CO}_2 \text{ eq.}$

The evaluation of greenhouse gas emissions using the calculation method based on the deductions of carbon dioxide emissions. The environmental impact of a product during its production can influence the material and process use because of the pollution; therefore, being able to choose other alternative materials which are less toxic, is desirable. Importantly, if the global warming potential is less than one, the material production does not have any negative impact on the environment. The impact assessment factor may influence the result based on the new regulation depending on the year of calculation and data.

3.6 Mechanical properties test

The mechanical properties of materials depend on their composition and microstructure. On this part, we evaluate how other factors affect the mechanical properties of composites materials, such as tensile, bending and the ability to perform under impact loading [218]. Material processing requires a detailed understanding of the mechanical properties of materials at different temperatures and conditions of loading [218]. For example, the mechanical behaviour of steels and plastics used to fabricate such item as aerodynamic car bodies can, therefore, be replaced with composite materials that have equivalent properties [218]. The mechanical properties have been carried out to estimate the tensile and flexural modulus of the composite material produced compared with other existing composite materials already on the market.

3.6.1 Tensile test

When taken beyond the elastic domain, tensile testing is a destructive test process that provides information about the tensile strength, yield strength, toughness and ductility of a material. Tensile testing presented in Figure 15 of composites is generally in the form of fundamental tension or flat-sandwich tension testing following standards such as ISO 527-4, ISO 527-5, ASTM D 638, ASTM D 3039, and ASTM C 297 [219].



Figure 15: Tensile test using Instron testing machine. The test used two jaws, to extend the sample that is held in the middle until rupture, the tensile test data is recorded through a computer system.

Tensile testing also provides tensile strength (at yield and at break), tensile modulus (i.e., Young's modulus), tensile strain, elongation, and percent elongation at yield, elongation, and elongation at break in percent, among other properties [201]. Tensile properties, such as tensile strength and tensile modulus of flat composites laminates, are determined by static tension tests in accordance with ASTM D3039-76. The tensile specimen is straight sided and has a constant cross-section with bevelled tabs adhesively bonded at ends. The tensile specimen is held in a testing machine by wedge action grips and pulled at a recommended cross-head speed of 0.02 cm/min until rupture. Longitudinal and transverse strength modulus are determined from the tension test data of unidirectional flax tapes.

3.6.2 Flexural test

The flexural test is conducted in compliance with the ASTM standard: D 790, the Instron testing machine (Figure 16) during a flexural test. Bending tests reveal the elastic modulus of bending, flexural stress, and flexural strain of material. The 3-Point bending involves placing the material across a span supported on either end of the material and bringing down a point source to the centre of the span and bending the material until failure, while recording applied force and crosshead displacement [220].



Figure 16: Flexural test using Instron testing machine. The bending test measured the maximum flexural stress for the three-point bend of the sample [202].

The modulus of elasticity in bending, or the flexural modulus (E) is calculated in the elastic region. The bend test often used for measuring the strength of brittle materials and the

maximum stress or flexural stress for the three-point bend test is given in Equation 10 [172]:

Equation 10: Flexural modulus E (GPa)

$$\text{Flexural modulus}(E) = \frac{L^3 F}{4w\delta h^3} \quad (10)$$

Where δ is the deflection of the beam when a force F is the load (N); L is the support span (mm) between the two outer points; w is the sample width (mm) and h is the sample thickness (mm). This test was conducted using a setup known as the three-point bed test [173]. Mechanical data indicates that for applications designed with respect to stiffness, flax fibre reinforced SMC (Short moulding compound) materials compete with glass fibre SMC, especially when the fibre length exceeds 25 mm [175].

3.7 Summary

Life cycle assessment (LCA) was carried out to evaluate the energy for producing composite material flax tape for industry. The project was performed with some energy usage measurements at the industrial partners' facilities. A standard domestic electricity usage monitor was used with a computer software to compile gate-to-gate (GtG) LCA data for the project. With the cooperation of partner, The University of Hertfordshire provided baseline data from the literature to inform and compare with their investigations.

The energy consumption of each process has been recorded following the same process. Electricity consumption collection is straightforward; however, the details of selection can be tricky during the process. Some data from the energy consumption was obtained from literature, and the carbon dioxide have been calculated using a conversion factor. The data for the energy consumption might be varied because there are distinct differences during the production process on the materials and parts.

The environmental impact over the life cycle investigated the calculation of energy used and carbon dioxide emissions produced. The natural fibre composite material (flax/PLA) has fewer processing steps to transform both materials into the tape, therefore, consuming less energy and producing lower carbon dioxide emissions over other synthetic material like glass and carbon fibre. The use of natural composite material has significant advantages on the reduction of greenhouse gas emissions. The thickness of the composite materials can have an impact on the energy consumption during the moulding process. Therefore, we can determine the new energy consumption under equivalent rigidity between flax/PLA and GFRTTP composites.

Chapter 4: Results

LCA gate-to-gate and processing technologies have been associated with the various design [221], relevant materials/products [222], decision making [223], waste management [224] and regional industrial ecology [225]. For these results, the focus will be on material transformations on flax/PLA in to composite tape and yarn/ tow glass in to triaxial glass fibre based on the energy consumption and carbon dioxide emissions. The results from the compression mouldings process were included through the LCA method GtG. Ecoinvent was used to extract the energy consumption and SimaPro software was used to produce a process tree of the manufacturing of the flax/PLA tape and triaxial glass fibre fabric including energy and carbon dioxide emissions. Therefore, through the process tree, environmental impact was estimated with Eco-indicator 99 (weighting). The mechanical and physical properties will be tested to compare and improve the environmental impact during the production process. SimaPro software was used to produce a process tree of the manufacturing of the flax/PLA tape and triaxial glass fibre fabric including energy and carbon dioxide emissions [115]. The mechanical and physical properties will be tested to compare and improve it during the production process.

4.1. Evaluation of the energy consumption of flax/PLA tape

The result of this graph was evaluated during the production process using a standard device (Ecoinvent) and computer software connected to the tape machine to determine the electricity and carbon dioxide emissions detailed on section 3.5.1. This method is a simple connection between the devices on the main electricity supply for the specific machine. The graph is producing automatically at the end of the process to show the electricity and carbon dioxide with times. The machine starts the production process with lower electricity consumption, over time the electricity increases progressively and becomes stable if there is no troubleshooting of the machine during the process. The electricity used for this process is 4.46 MJ/h for a production of 240 m of 60% flax/40% PLA. The carbon dioxide emissions (Figure 17) increase with the energy consumption during the experiment with time (h).

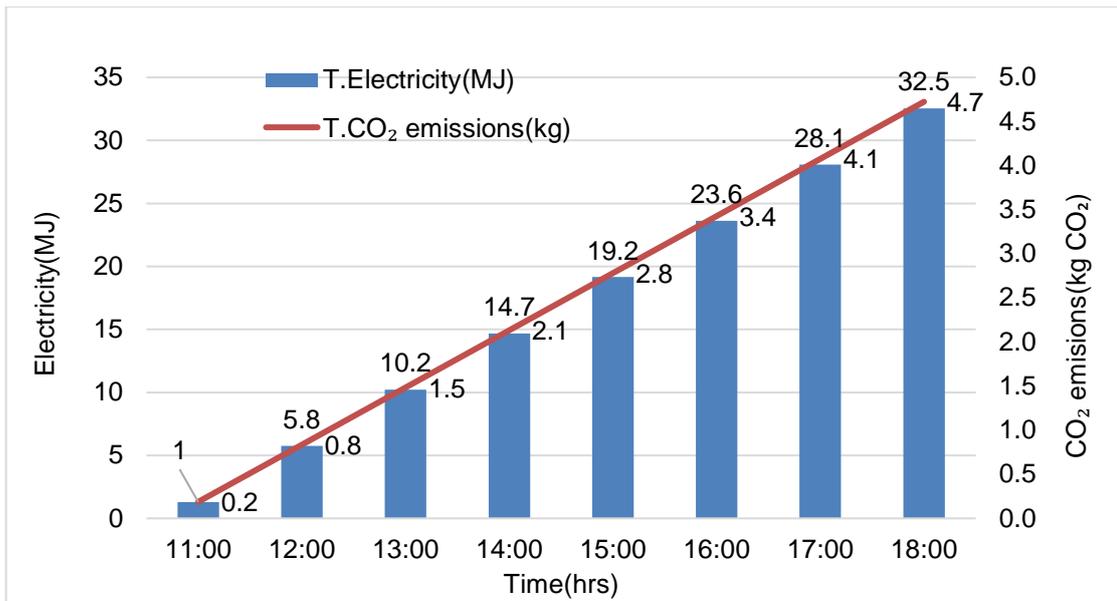


Figure 17: Tilsatec (T): Daily electricity used on a tape machine during a single manufacturing process. The electricity and carbon dioxide emissions increased over time during production.

The trend line and bar chart shows the daily electricity for eight hours production and the increasing carbon dioxide emissions over the time during production. The computer system software analysed the electricity use during a single production process and estimated the peak point and stable condition of the electricity. It was found that the electricity used at the end of production was valued at 4.46 MJ/h and carbon dioxide emissions of 0.65 kg.

Table 15 gives information about the daily (assuming 8 hours per days) and yearly (assuming 254 working days excluding weekend and bank holidays) production of flax and PLA. The tape machine uses purchase electricity; the daily electricity consumption is estimated at 32.54 MJ/h and CO₂ emissions at 4.72 kg. The number of materials produced per year is estimated at 123.516 t/year, purchase electricity is valued at 11877.1 MJ, producing carbon dioxide emissions of 1362.9 kg.

Table 15. Energy consumption for a single production estimation of flax tapes. The evaluation of the electricity and production of composite tape in working day and year (assuming 254 working days a year).

Production	Composite Tape length produced (m)	Electricity used (MJ)	CO ₂ emissions (kg)
Daily production (8hrs)	1920 (338.4kg/day)	32.54	4.72
Yearly production	487680 (86 t/year)	8265.16	1199

The production of composite materials flax and PLA can be uncertain depending on the tape machine speed, setting and the data may not be the same. Therefore, the energy was evaluated per hour daily and calculated per number of day per year. This is to forecast energy consumption and production.

4.1.4 UD composite tape manufacturing process (flax/PLA)

The process consists of selecting a percentage of flax and polylactic acid or Maleic Anhydride Polypropylene and blended to produce a unit directional composite tape materials (Figure 18). The electricity used has been recorded to estimate the energy consumption and CO₂ emissions.

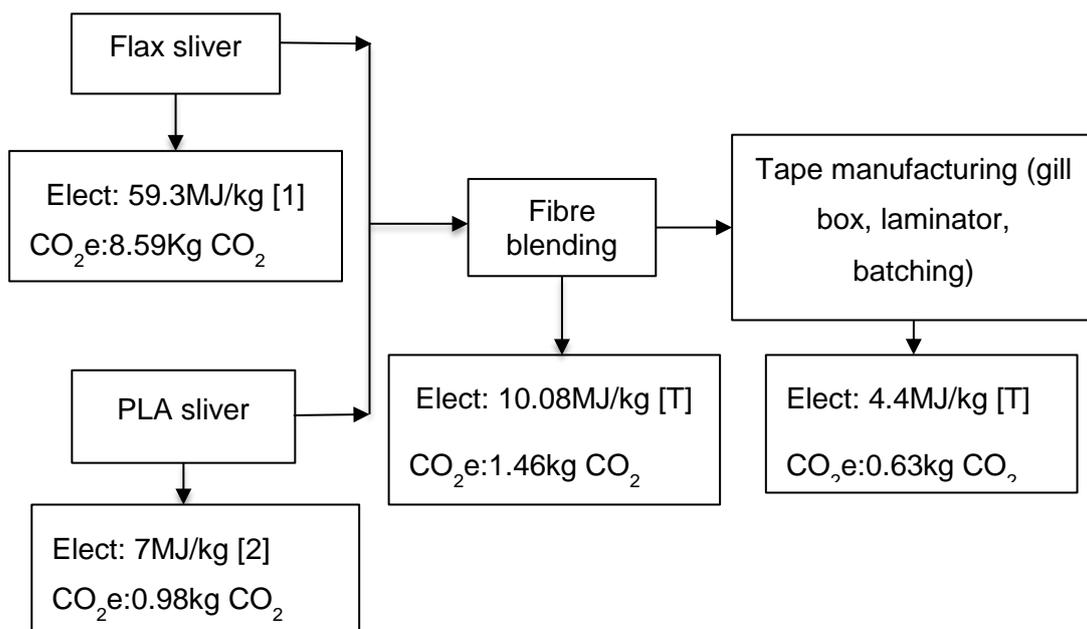


Figure 18: The manufacturing process and the energy consumption of 100 m of 170 gsm Flax/PLA UD from Tilsatec (T). The energy consumption and carbon dioxide emissions were added to each process of manufacturing to identify the high energy intensity.

The simulation in the processing of composite flax/PLA tape consists of inputting the energy consumption of the material and process on SimaPro 8. This generates the process tree (Figure 19) to show the energy consumption and thermometer levels of the carbon dioxide on the simulation.

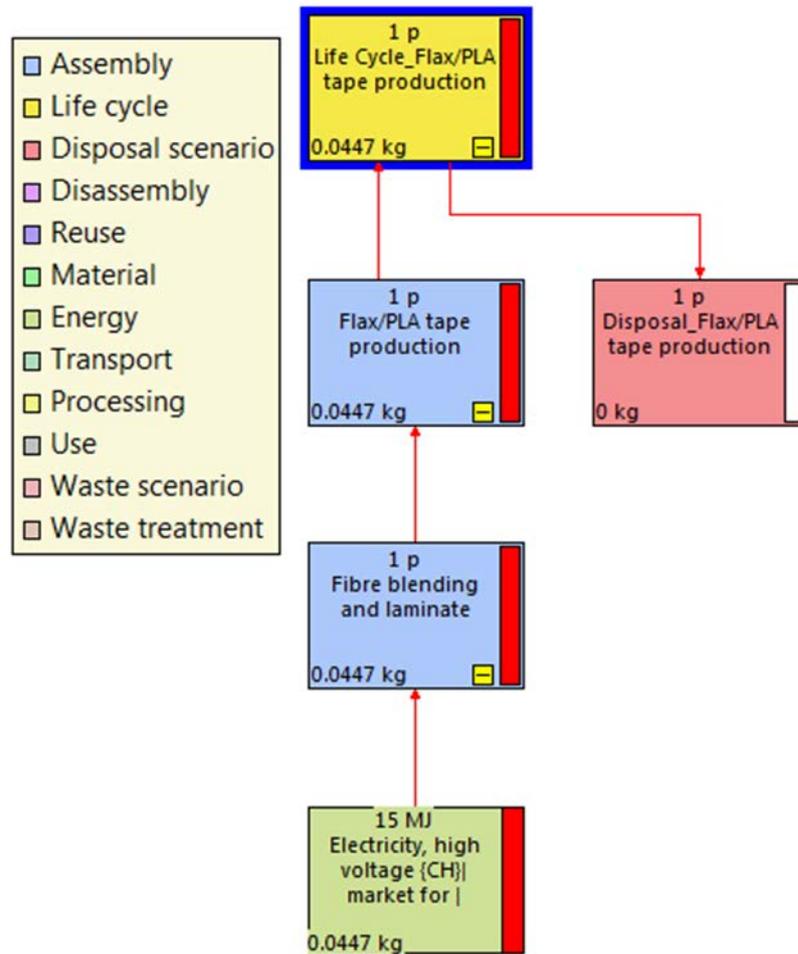


Figure 19: SimaPro 8 simulation LCA for the production of flax/PLA tape. The simulation process of flax/PLA tape is shown with a different square colour at each level of the output. The red column reveals the concentration of carbon dioxide emissions, which is estimated at 0.0447 kg CO₂e.

In this method, only the energy inputs of the flax/PLA tape and the environmental impact are evaluated. The red column shows the thermometer of the manufacturing process; for example, fibre blending and laminated is 0.0447kg carbon dioxide produced for this process. The simulation shows that the process produces lower CO₂ emissions of less

than 1%. The green colon line on disposal and reuse tapes have a lower environmental impact of the flax tape at 0.01% pollution. Therefore, it is an environmentally friendly material.

4.2. Evaluation of the energy consumption of triaxial glass fibre

The electricity on the left side and carbon dioxide on the right side and linked to time during the production. The red line indicate the increasing carbon dioxide emissions and the blue column indicates the electricity usage in function of time. The electricity consumption was evaluated at 23.76 MJ/h, and CO₂ emissions at 3.45 kg. The bar chart (Figure 20) indicates the electricity and the trend line of the carbon dioxide emissions during production.

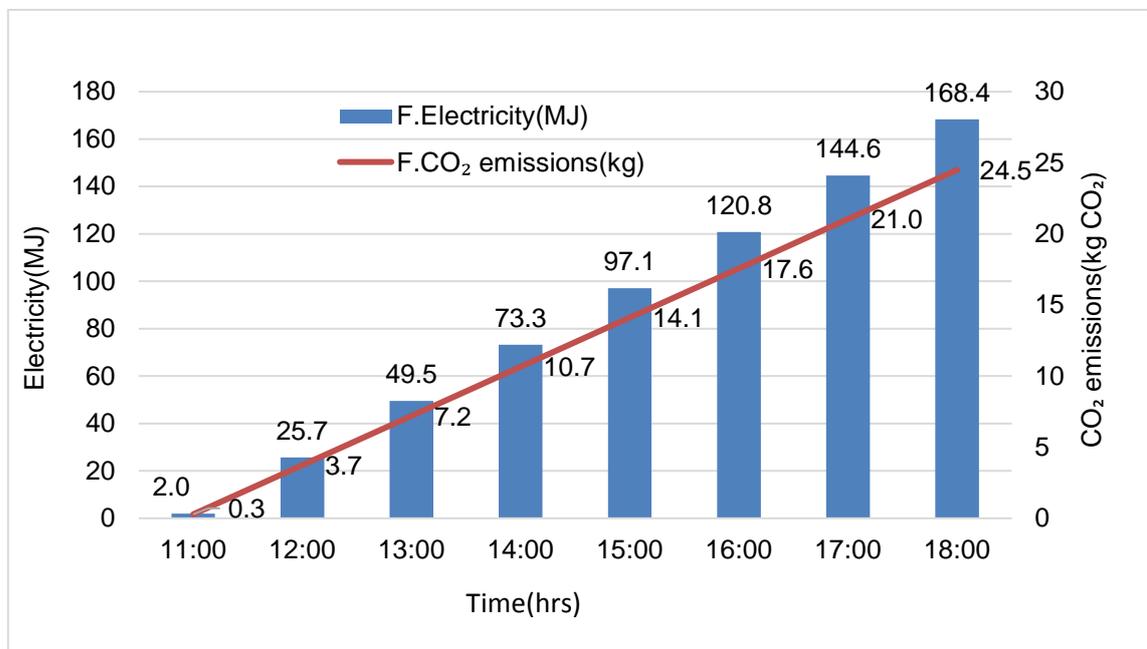


Figure 20: Daily energy consumption and carbon dioxide emissions. The electricity is evaluated at 168.4 MJ and the carbon dioxide emissions at 24.5 kg CO₂ for 8 hours of production (Formax).

The daily electricity used for one single process during the production of glass fibre fabrics and carbon dioxide increased with time during production. Therefore, daily energy consumption can be estimated at 168.38 MJ for 8 hours production with a carbon dioxide emission of 24.5 kg CO₂e. The production rate is 0.5 kg per minute of approximately 30kg/h equivalent to 0.8 MJ/kg of triaxial glass fibre fabric. The evaluation (Table 16) can be estimated per day and year, assuming 8 hours work per day excluding bank holidays and weekend.

Table 16: Production of glass fibre fabric depending of the machine 5 on Formax. The estimation of the electricity and production of composite glass fabric in working day and year (assuming 254 working days).

Average production	Triaxial length produced(m)	Electricity used(MJ)	CO ₂ emissions(kg)
Daily(8hrs)	480	168.4	24.5
Yearly	121920 (21.5t/year)	42774	6223

The energy consumption and carbon dioxide emissions increased in function with the production, therefore, this has an impact on the environment. The triaxial glass fibre is a thin layer of Yarn/Tow that was transformed in fabric material for the automotive and aerospace industry.

4.2.1 UD glass fibre yarn process

The average electricity obtained at each stage of the production process, shown in Figure 21, represents the production of the raw materials glass, sand and borate into UD glass on Appendix A section 10A, 11A and 12A. Glass fibre or Carbon fibre is made by combining raw materials. The start with the process of melting them in a three-stage furnace, extruding the molten glass through bushings in the bottom of the forehearth, cooling the filaments with water, then applying a chemical size. The filaments then are gathered and wound into a package [9]. The weaving and stitching process of the energy consumption was obtained by direct measurement during the manufacturing of the triaxial glass fibre in Formax (F).

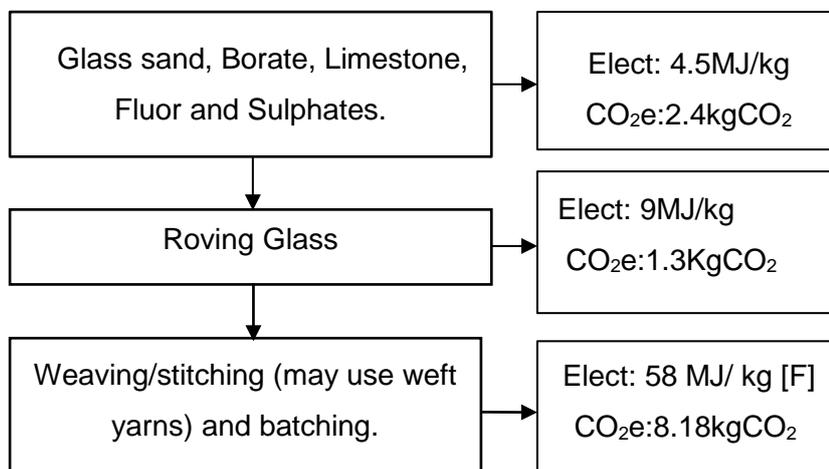


Figure 21: The process of UD glass fibre shows the energy that is used at each step e.g. roving glass and weaving/stitching. The electricity consumption may vary for each method depending on the technology [10].

The glass production uses electricity or gas intensively for each step of the transformation. The electricity consumption may vary for each process depending on the machine and process. During the production process to transform glass into triaxial fabrics, most of the electric appliance has to be covered to avoid any spark that may cause a fire. The total electricity consumption is evaluated at 58 MJ/kg, for a production rate of 600 g per 1.27 m wide. Therefore, the Simapro used the data to develop the process tree presented in Figure 22. The input and output are known as gate-to-gate to seek maximum energy use. This action by one phase may have the result of raising resource consumption, such as electricity and emissions for the manufacturing process, due to the production of the composite material part on a particular machine for a single production.

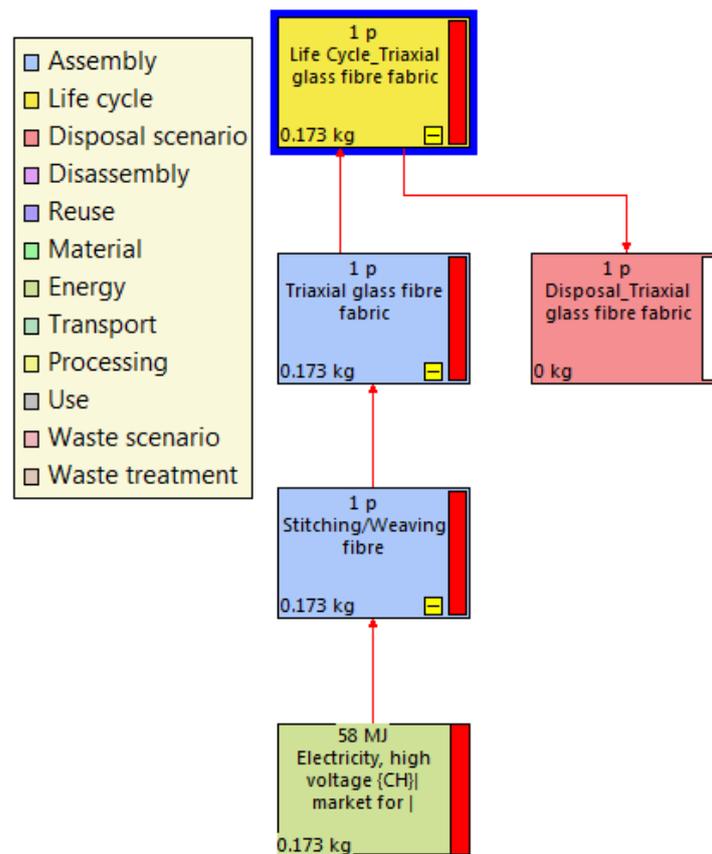


Figure 22: SimaPro 8, LCA energy consumption and carbon dioxide emissions for one process. The simulation process of triaxial glass is shown with a different colour at each process.

level of the production. The red column shows the level of the carbon dioxide emissions which are estimated at 0.173 kg CO₂e.

In this method, only the energy inputs of the glass fibre and the environmental impact are evaluated. The vertical red column, shows the thermometer of the manufacturing process, for example 0.173 kg of carbon dioxide is produced, when manufacturing triaxial glass fibre fabric in this process. The simulation shows that the process produces higher CO₂ emissions of more than 1%. The green colon line on disposal and reuse tapes have a lower environmental impact of the flax tape at 0.01% pollution. Moreover, the triaxial glass fibre is not a biodegradable material; more processing needs to be investigated to recycle triaxial glass fibre.

4.3. Energy consumption that contribute to manufacture composite material

The energy consumption was estimated for the air compressor, heat for the air compressor and vacuum pump during single manufacturing. All of these processes contributes to the production of composite material part. And the energy can vary depending on process and technology.

4.3.2. Energy consumption for air compressor

Compressed air is the second form of energy consumed in the manufacturing industry, although the most expensive, it is often treated with less importance than it deserves [226]. Compressed air for the manufacturing industry can have numerous applications as energy form, such as drill, cut open shut, push, pull, paint, clean, blow, mix, etc. For this part, the focus will be on pneumatic systems. Pneumatic systems use compressed air to transmit power through cylinders or pneumatic motors [226]. Specifically for the moulds and tools industry, compressed air is essential for the following activities: tool powering, clamping, controls and actuators, forming, mould press powering, cooling system [226]. Compressed-air generation is energy -intensive, for most industrial operations, the energy cost fraction of compressed air is significant compared with overall energy costs. The air compressor is just an air pump, used in composite material for suctioning the air into a vacuum, bagging the laminated composites [227, 228]. The air compressor for composite material uses the input side for suction, rather than using the output side for blowing. The electricity use for a single process was estimated with no conventional material in Figure 23.

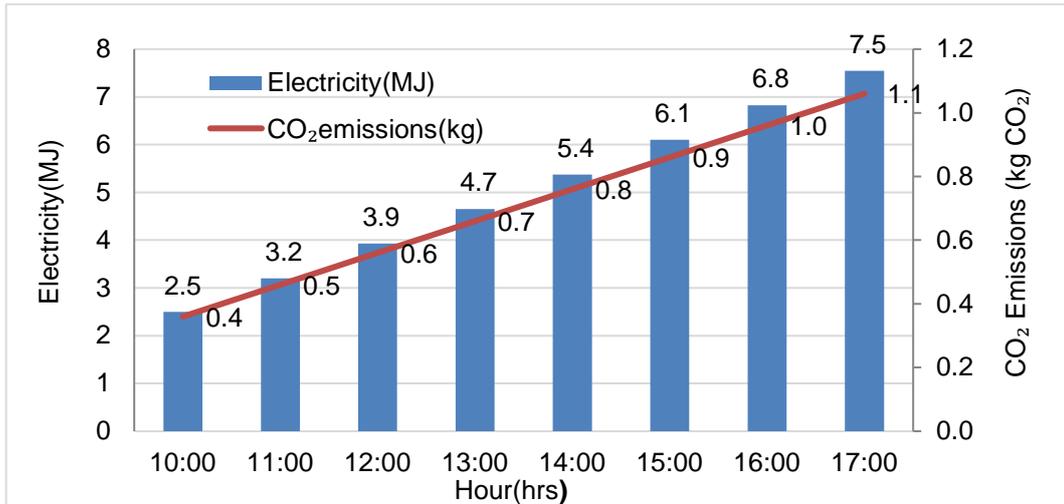


Figure 23: Axon automotive: Daily electricity use of air compressor for a single process. The bar chart illustrates the electricity generated during manufacturing of the part, using an air compressor for the process. The air compressor is used for resin transfer moulding to produce high-quality composite materials part using a vacuum bag.

The chart illustrates the electricity generated during a single production process, using an air compressor for manufacture a component. At the beginning of the process, the electricity is very low and increases over time. Over the next 8 hours, the electricity generated was estimated at 0.58 MJ/kg and CO₂ emissions at 1.06 kg. The average electricity used for a single process was valued at 0.05 MJ/kg and less than 0.1 kg of carbon dioxide emissions. The energy intensity represents energies associated only with process producing 500 g of material product per hour. Cycle time assumption is 1h per product.

4.3.3 Energy consumption for heat

In the composite material, heat is used for dual purposes, with an air conditioner and more particularly, by utilising the air conditioner with a heat pump to cool down the component or to assemble composite parts. During the manufacturing process, the heat is used to produce a part. The electricity was recorded for a single process with the machine on for 8 hours, without adequate materials. The red line represent the carbon dioxide emissions and the blue column represent the electricity (MJ) during the production.

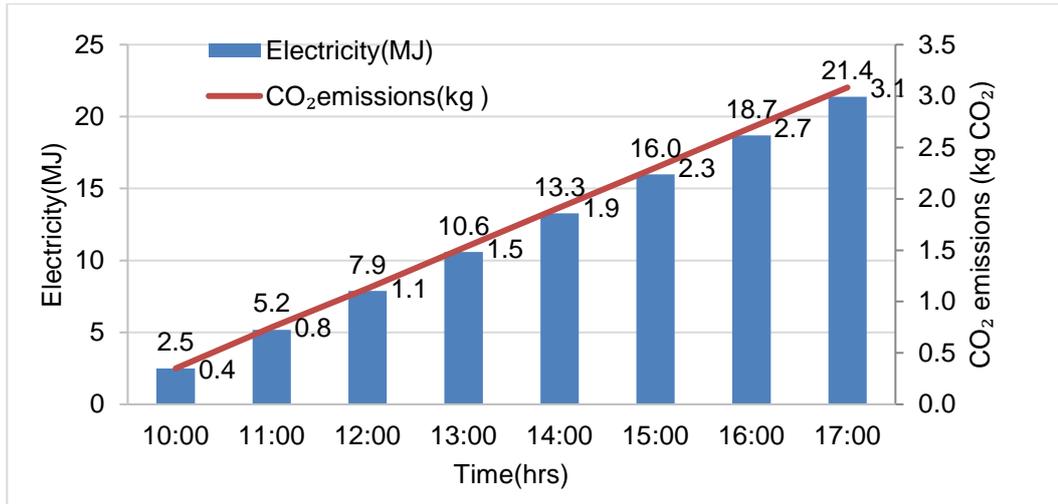


Figure 24: Axon automotive: Daily electrical use of heat exchange for air compressor during manufacturing. The electricity was used to increase the thickness of the composite material by using a hot air connected to the air compressor. Therefore, energy intensity rose over time.

The chart illustrates the electricity generated during a single production process, using heat to manufacture a component. At the beginning of the process, the heat is turned on to reach a specific temperature. Over the next 8 hours, the electricity generated was estimated at 21.20 MJ and CO₂ emissions at 3.08 kg CO₂. The average electricity used for a single process was valued at 2.66 MJ hence carbon dioxide emissions were 0.38 kg CO₂.

4.3.4 Energy consumption of vacuum pump.

The heart of a vacuum system is the vacuum pump. The powered vacuum pump is mechanically similar to air compressors but works in reverse so that air is drawn from the closed system and exhausted to the atmosphere. Vacuum pumps are designated by their vacuum pressure potential, their displacement in cubic feet per minute (CFM) and the horsepower required to drive the pump [229]. This vacuum level translates to the highest amount of work clamping pressure that can be generated [229]. For example, if we are vacuum bagging a one square foot laminate, a 20" Hg vacuum will yield ten psi clamping force or a total of 1440 pounds of clamping force over the entire laminate. If we are laminating a 4'x8' panel, the same 20" Hg (10psi) will yield over 46000 pounds of clamping force spread evenly over the entire panel [229]. The electricity used for this process is estimated at 1.94 MJ and CO₂ emissions deducted at 0.28 kg CO₂.

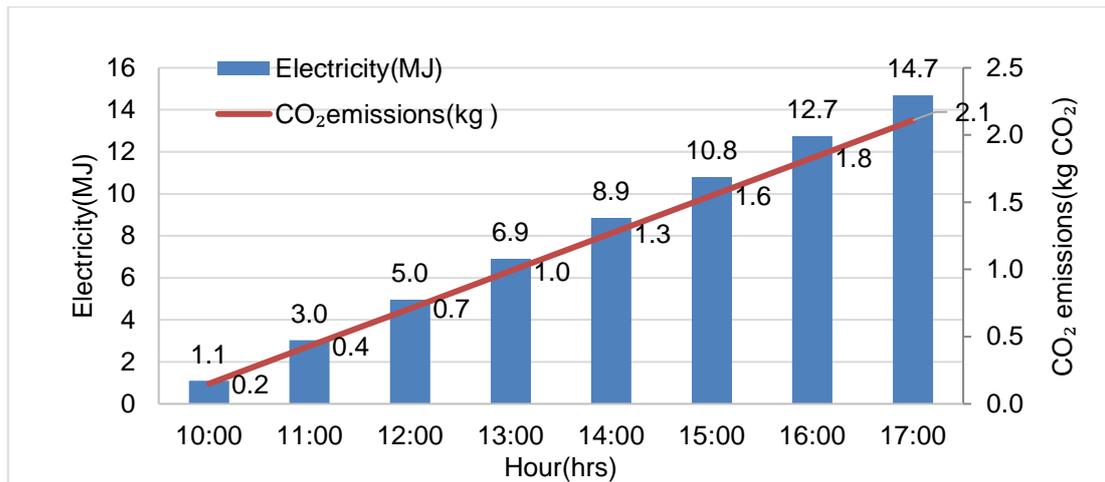


Figure 25: Axon automotive: Daily electricity use of the vacuum pump during manufacturing (Source: Axon Automotive). The bar chart illustrates the electricity generated during a single production process, using a vacuum pump for curing a part.

The chart (Figure 25) illustrates the electricity generated during a single production, using a vacuum pump for manufacturing a component. At the beginning of the process, the electricity is very low and increased with time. Over the next 8 hours, the electricity generated was estimated at 14.68 MJ and CO₂ emissions at 2.11 kg. The average electricity use for a single process was valued at 0.15 MJ. Most of the data results have been obtained based on the machine that was used to produce a composite materials components. Table 17 shows the process and total energy consumption use, for composite flax tape, during batch production.

Table 17: Energy consumption for the prepreg process. The total energy consumption was estimated using an air compressor, heat for the air compressor and vacuum pump were considered for the production of the component.

Prepreg	Energy consumption (MJ)	Carbon dioxide emissions (kg CO ₂ e)
Air compressor	0.05	0.1
Heat for air compressor	2.66	0.38
Vacuum pump	1.94	0.28
Total energy	4.65	0.76

The total energy consumption for 0.5 kg of the composite Flax/PLA tape was evaluated at 4.65 MJ and carbon dioxide at 0.76 kg CO₂e. The energy consumption might increase

with different processes if a mass production used machinery. In this case, the process was hand lay up for a small amount of material and then dry with hot air in a vacuum chamber.

4.3.5 Energy consumption of compression moulding

The bar chart in Figure 26 shows the electricity generated during a single production process of moulding to manufacture a prepreg FL/PLA sheet composite material. At the beginning of the process, the electricity is very low and increased with time. Over the next 8 hours, the electricity generated was estimated at 137.12 MJ and CO₂ emissions at 19.91 kg. The energy intensity represents energies associated only with process producing 500 g of material product per hour and the cycle time assumption is 1h per product.

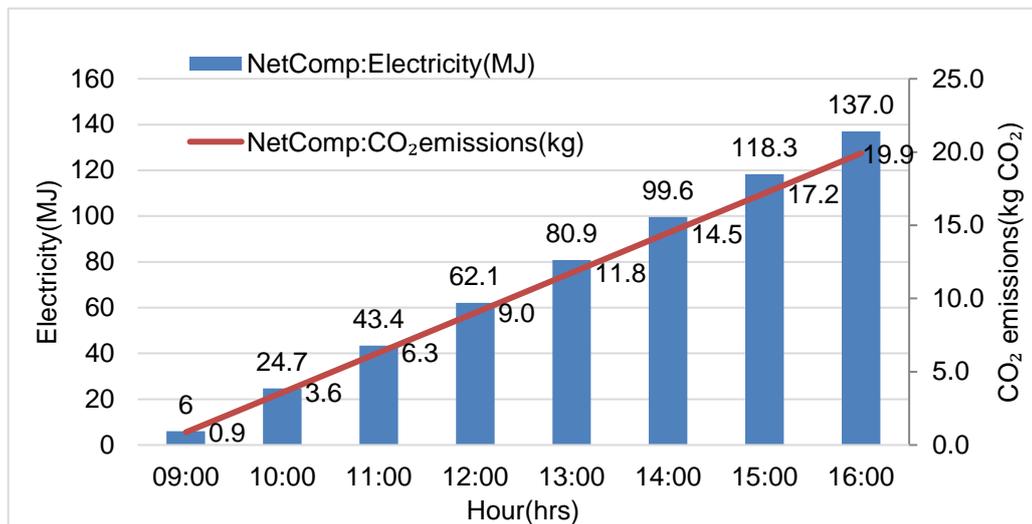


Figure 26: Flax/PLA Prepreg flax moulding process electricity and CO₂e consumptions while moulding. The bar chart illustrates the electricity generated during a single process for hot press and coolant for the production of moulding to manufacture a prepreg composite Flax/PLA sheet material. The electricity used for this unique method is at 18.7 MJ hence CO₂ carbon dioxide is approximately 2.64 kg CO₂e.

The data provides information regarding the energy consumption and carbon dioxide emissions of the moulding process of the composite flax/PLA tape for eight hours of production. The electricity patterns bounced during production process with time, therefore the carbon dioxide rose over time; meaning the carbon dioxide emissions depend on energy consumption during the process. The simulation, presented in Figure 27, of the moulding process for composite flax/PLA tape consists of inputting the energy consumption of the material and process on SimaPro 8. Then, they generate the process

tree with energy consumption and thermometer indicated the amount of the carbon dioxide.

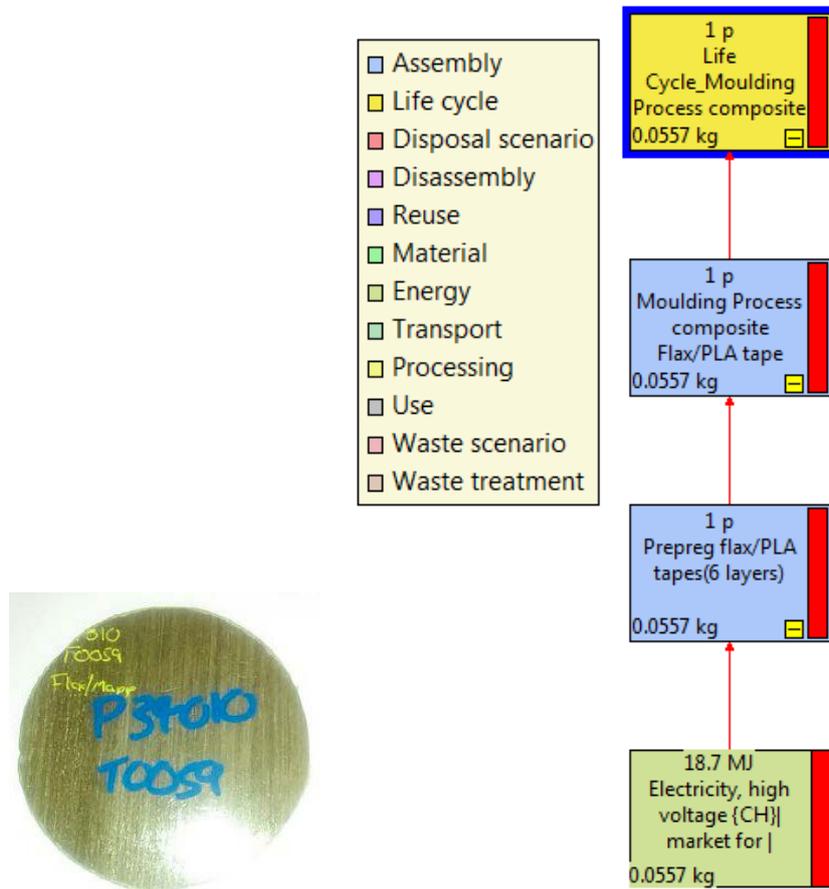


Figure 27: SimaPro 8: simulation of the moulding process of composite flax/PLA tape. The simulation process of the prepreg flax/PLA is shown with a different colour at each level of the production. The red column shows the level of the carbon dioxide emissions which were estimated at 0.0557 kg CO₂e. The sample beside shows a compression moulding of prepreg composite flax/PLA tape 60/40 per cent.

The compression moulding of composite flax/PLA tape and the environmental impact were evaluated. The energy consumption is estimated at 18.7 MJ for one process. The red column shows the thermometer of the manufacturing process; for example, fibre blending and laminated is 0.0557 kg of carbon dioxide produced for this process. The simulation shows that the process produces lower CO₂ emissions of less than 1%. The LCA composite moulding process for glass fibre are the same process that the composite flax/PLA on the same moulding machine. Therefore, energy consumption to produce

moulding part for glass fibre is high that composite flax/PLA tape. The input energy used to produce the composite material during the moulding process is 19.5 MJ.

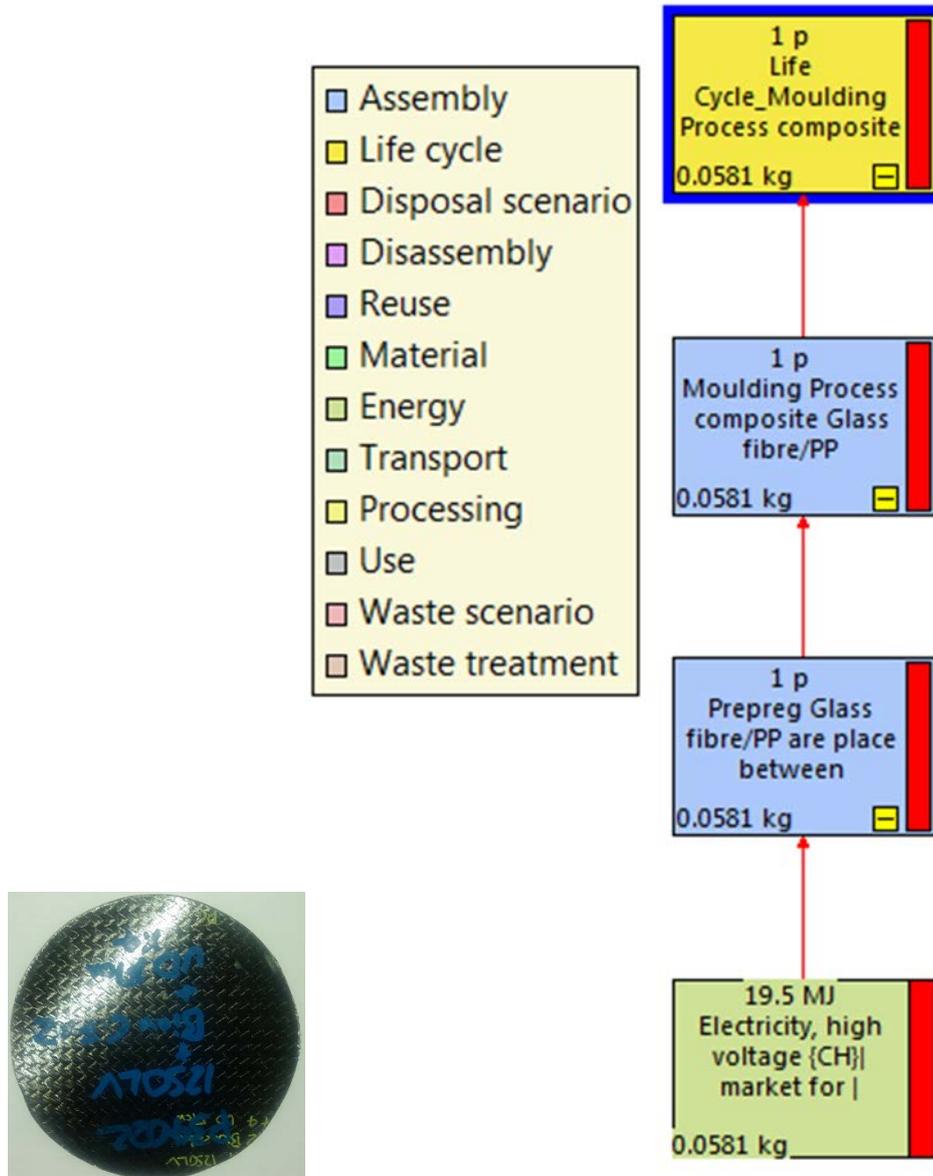


Figure 28: SimaPro 8 simulation of moulding process of composite glass fibre/PP. The simulation process of the prepreg glass Fibre/PP is shown with a different colour at each level of the production. The red column shows the level of the carbon dioxide emissions which is estimated at 0.0581 kg CO_{2e}. The sample beside shows a compression moulding of prepreg glass fibre/PP.

The compression moulding of composite glass/PP and the environmental impact are evaluated. The red column in Figure 28 represents the thermometer of the manufacturing process, for example, moulding process of glass/PP produces 0.0581 kg of carbon dioxide production for this process. The simulation shows that the process produces CO₂

emissions that have an impact on the environment. When the energy consumption increases, the carbon dioxide emission increase as well. Table 18 summarises various manufacturing processes, energy consumptions and carbon dioxide emissions.

Table 18: Energy consumption for various materials and processes. The energy intensity for the fibre production, fabric production and prepreg process was evaluated and may vary depending on process and technology.

Materials	Energy Intensity (MJ)	CO ₂ Emissions (kg CO ₂)	References
Glass fibres	13–32	1.8–4.6	[98]
China reed fibres	3.6	0.5	[98]
Flax fibres	6.5	0.9	[160]
Process analysis			
Fibre production	12.24	1.7	[98]
Fabric production	0.772	0.1	[165]
Prepreg production	40.0	5.8	[165]
Resin production	34.2	4.9	[165]
Flax tape fabric	12.25	1.7	Tilsaltec
Triaxial glass fabric	29.04	4.2	Formax
Glass fabrics manufacturing	30.84	4.5	[165]
Prepreg material production			
Prepreg flax tape component	64.49	9.3	Tilsaltec, [165]
China reed fibre-epoxy	56.61	8.2	[168]
Glass fibre-epoxy	83.84	12.18	[168]
Triaxial glass fabric-Epoxy	82.04	12	Formax [168]

This process provides some of the direct electricity of the materials under processing, and so we can deduce the quantity of carbon dioxide emissions based on the eCoinvent eLink software. These results can then be used on SimaPro Software 8 to simulate the manufacturing process by inputting and outputting the data. In this work, a process for gate-to-gate on flax/PLA and glass fibre non-woven fabric production was developed for collecting production data for the analysis by using two primary methods: The E2 Link Classic and SimaPro Simulation packages. E2link classic allows recording the direct energy consumption and carbon dioxide emission during the production of composite materials. SIMAPRO was used to simulate the manufacturing process and to analyse the

impact of manufacturing during production. After that, the data can be used to estimate the cost, CO₂ emissions produced, and energy consumption needed to provide a natural composite material. The treatment of electrical usage data is a crucial key point in energy intensity analysis for each GtG manufacturing of composite materials.



Figure 29: Axon automotive: Application of the composite material in the automotive industry, such as BMW, improves the strength of the hybrid car body sheet metal and composite glass fibre which reduces the weight of the car for better fuel efficiency.

The production of the car in Figure 29 uses composite material and techniques to produce a lighter conventional car. Subsequently, the production process produce less energy than conventional manufacturing car, therefore creating less carbon dioxide.

4.4 Environment impact of the production of composite fabrics

The environmental impact potential is the weighted sum of the product of individual pollutant emission and their characteristic factors. However, specific environmental impact potential cannot be directly compared with others due to the different units. Therefore, different environmental impact potentials should be normalised and weighted to evaluate the environmental impact load (EIL) for the product/service [230].

For the production of composites Flax/PLA tape, the operations involve, heating, blending and laminating on the tape machine to reach the final product. The total energy consumption of fibre blending and tape manufacturing, life cycle gate-to-gate is estimated at 15 MJ/kg and carbon dioxide emission at 0.0557 kg/CO₂. As long as the production of flax/PLA tape fulfils aesthetic expectations and dimensions are met, the process to produce composite flax/PLA tape has succeeded with lower energy consumption. Moreover, the energy consumed to produce triaxial glass fibre can be used to produce 40% more composites Flax/PLA tape material. The energy for both cultivation and

transportation was not considered for the harvest of flax, which has shown a less environmental impact on water and earth.

Moreover, the life cycle assessment impacts for the production of flax/PLA tape and triaxial fabric. Figure 30 and 31 shows low emissions on the environment based on the eco-indicator 99 weightings, depending on the sum of materials produced. The production of composite material shows the different area of environmental impact depending on the type of composite material created; for example, climate change for flax/PLA tape is lower than that of triaxial glass fabric. This is due to the different manufacturing process and method to produce different composite materials. By creating a large number of materials, with lower environmental impact and to provide a high amount of composite material, this manufacturing will have less impact on the environment.

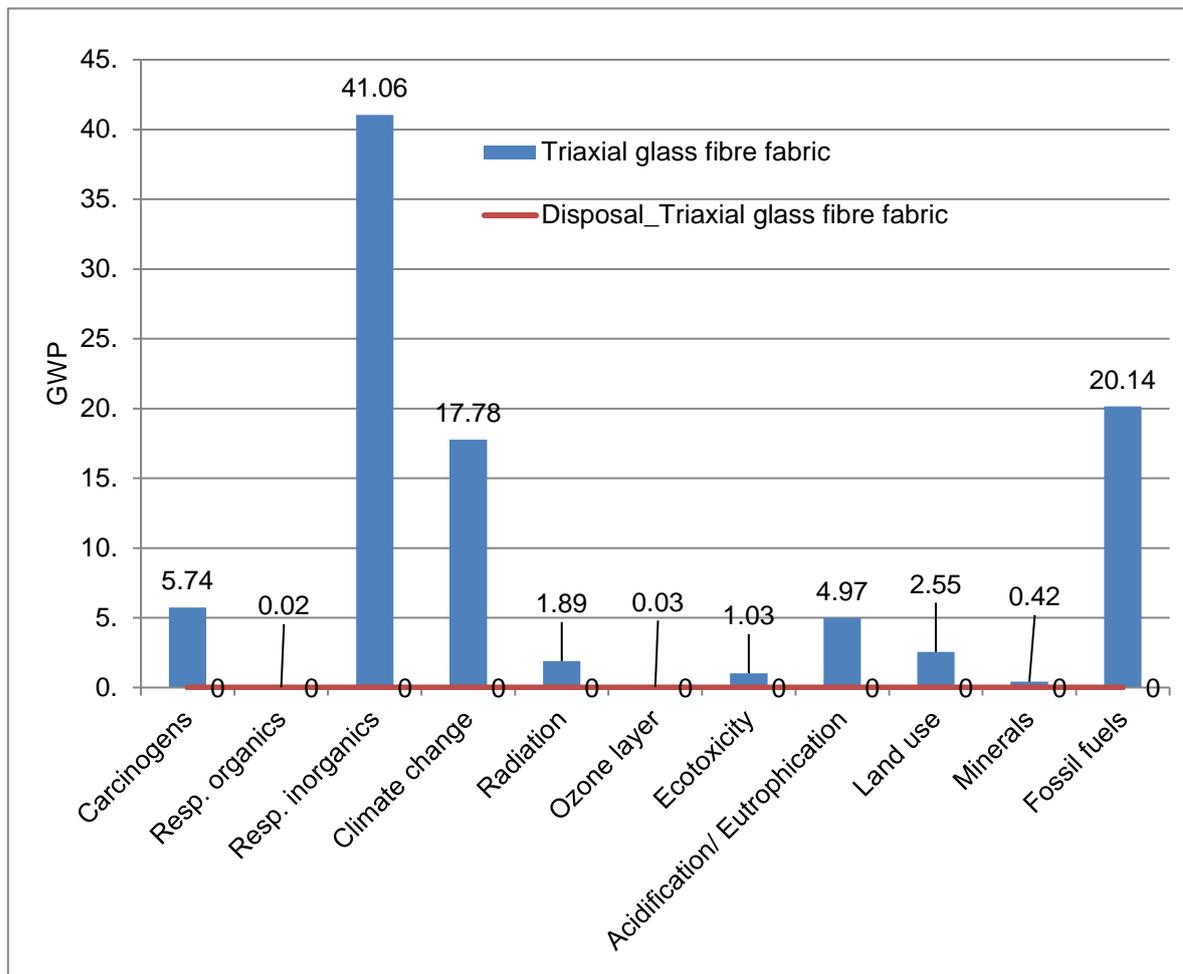


Figure 30: Analysing 1p (process) `Life Cycle Triaxial glass fibre fabric`; Method: Eco-indicator 99 (H) V2.10 / Europe EI 99H/A/ weighting /excluding long-term emissions.

The high impact of triaxial glass fibre is between eight elements, responsible inorganic with 41.05 kg CO₂. Inorganics and the lower impact is Eco-toxicity with 1.03 kg CO₂. Others environment impact is less than one and is not taken into account. The higher environmental impact of the flax/PLA varies between five elements, the responsible inorganic of 10.61 kg CO₂ and 1.28 kg CO₂ acidification. The global warming potential depends and varies about the electricity production and uses.

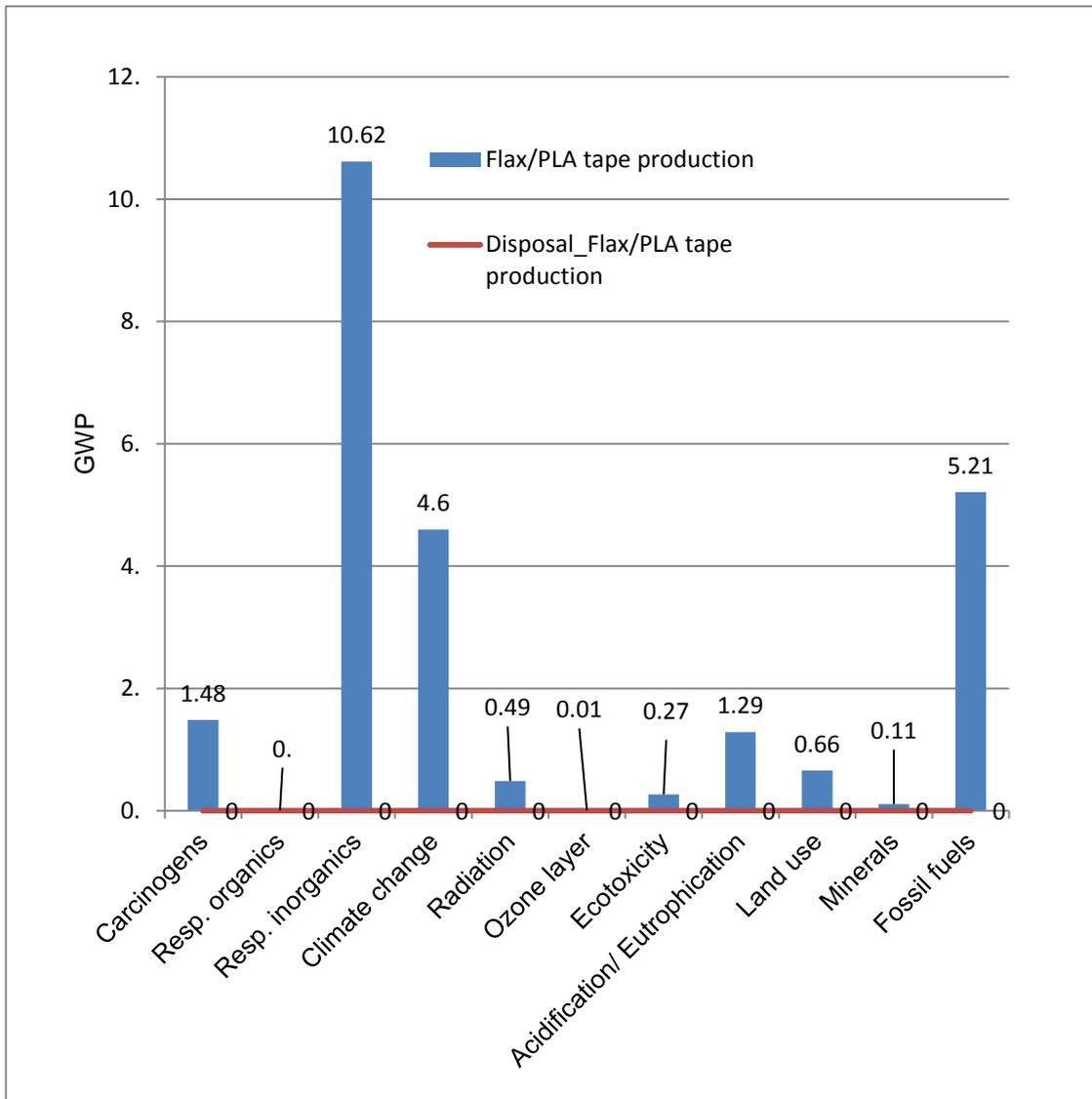


Figure 31: Analysing 1 process 'Life Cycle flax/PLA tape production'; Method: Eco-indicator 99 (H) V2.10 / Europe EI 99H/A/ weighting /excluding long-term emissions.

We found that their environmental impacts for the natural fibre composite are dominated by the energy and responsible inorganics. Another elements like mineral, land use, responsible organic, radiation and eco-toxicity are lower than that for triaxial fabric. Even though natural fibre accounts for 66% of the volume of the component, it contributes only

5.3 % of the cumulative energy demand [231]. All emissions are sorted into classes according to the effects they have on the environment. For example, the climate change or global warming can be attributed to our reliance on industrial activities over the years. This is because the manufacturing of materials is directly connected to the amount of carbon emitted in consuming the electrical energy for that manufacturing process. Over the years gases are able to absorb radiation from the sun, they have a direct impact on the temperature of the planet causing acid rain acidification / eutrophication.

The life cycle gate-to-gate can only be one of the references for the manufacturers and decision-makers, since the weighting factors for different environmental impact categories depends on subjective expert opinion. On the other side, the gate-to-gate assessment of the flax tape does not include the product use and end-of-life phases, which limits the ability to identify the burden-shifting. It was clear that boundary selection had a significant influence on the gate-to-gate observed results. In this study, the manufacturing requirements to use flax, PLA and glass fibre input to produce composite materials with flax tape and triaxial glass fibre used purchased electric. The consumption of electricity would lead to energy consumption and carbon dioxide production based on the recent series of ISO standards 14040 to 14043.

The results obtained show that PLA commingled well with flax, as a matrix material for natural fibre composite. The energy consumption is estimated at 0.25 MJ/kg for the production of flax tape and 0.8 MJ/kg for triaxial glass fibre fabrics. Therefore, the production of composite flax tape uses less energy than some materials already being used in the industry. They are cheaper to produce, and the processing technique is not complicated as much as the conventional products. The process of commercial production of composites flax/PLA tape is promising based on the manufacturing process and environment impact.

4.5. Environment impact of the production of composite moulding

The environment impacts to produce a composite part using composite flax/PLA tape and glass fibre/PP was evaluated. Three impact assessments were produced to measure the impact on the environment, such as human health, ecosystem quality and resources. We can see that composites such as flax/PLA have a lower environmental impact than Glass/PP during the moulding process base of the energy consumption produces.

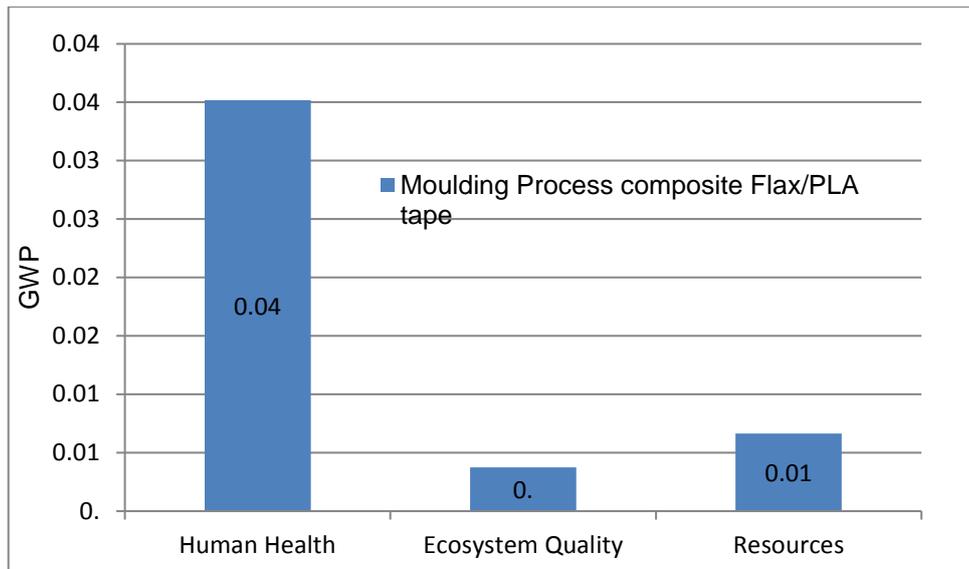


Figure 32: Simapro 8 for LCA, analysing 1p (process) `Life Cycle_ Moulding process flax/PLA tape `; Method: Eco-indicator 99 (H) V2.10 / Europe EI 99H/A/ weighting.

The environmental impact are related to human health, ecosystem quality and resources during the moulding process of composite flax/PLA. The environment impact of composites flax/PLA tape fabric moulding process is less than one; therefore, no significant consequence on the three-element on the figure above. We can see the global warming potential vary between 0.03 and 0.006 kg CO₂ and the higher element is human health. The weighing factor for the production of natural fibre composite material had a lower impact assessment therefore represented a lower risk for the production as long as most elements were lower that one. This prediction can be helpful for future decision making regarding the production of composite materials.

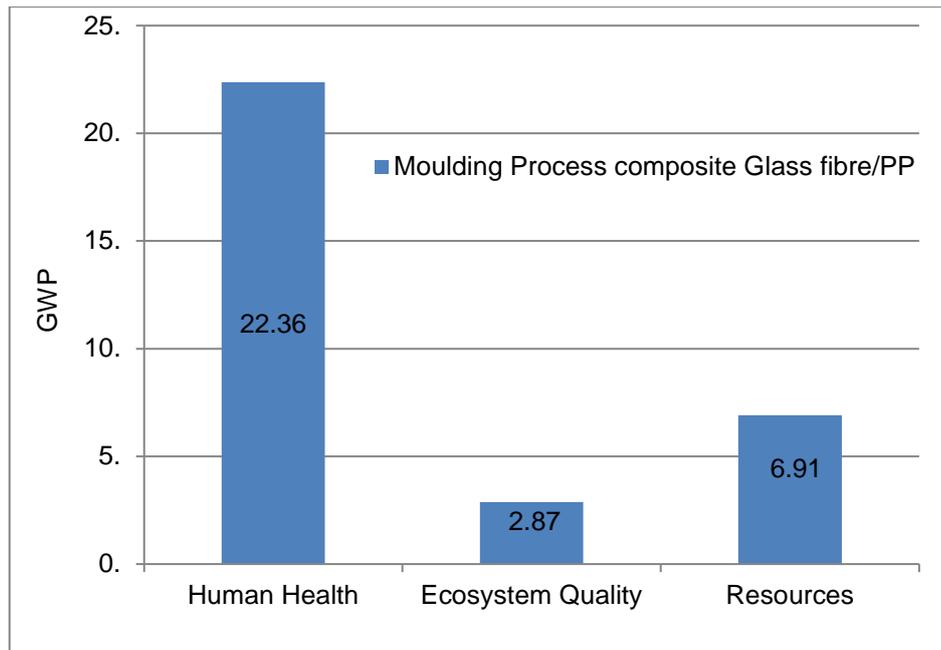


Figure 33: Simapro 8 for LCA, analysing 1p (process) `Life Cycle_ Moulding process composite Glass fibre/PP`; Method: Eco-indicator 99 (H) V2.10 / Europe EI 99H/A/ weighting.

The environmental impact of the moulding process evaluates three assessment impacts (human health, ecosystem quality and resources) that can be productive during the moulding process of composites glass/PP. The human health represent 22.36 kg CO₂ and the global warming potential followed by resources 6.91 kg CO₂ and ecosystem quality 2.87 kg CO₂, because of the nature of the synthetic materials. The sum of the total environmental impact is less than one, meaning that carbon dioxide emissions are negligible. The energy consumption to produce a composite material using the prepreg process is estimated at 14.4 MJ for flax/PLA tape, 44.48 MJ for glass fibre fabrics and 72 MJ for polypropylene. From this study and specific applications, natural fibre reinforcement (NFR) composites have lower environmental impact than glass fibre reinforcement (GFR) composites on most performance metrics. However, there are significant differences, regarding the specific component/application being studied, in addition to the material composition of the referenced component, as well as the NFR component and specific natural fibre chosen. This is also affected by production processes, boundaries and scope of the life cycle assessment, as well as environmental impacts considered, and the data sources used. This systematic process help to take into account the environmental impact assessment of human activities on the environment.

4.6 Mechanical properties

The mechanical properties of flax/PLA and flax/MAPP were assessed with the collaboration partner Net composites to improve the mechanical properties of the natural fibre through manufacturing. The sample was prepared following the ISO standard of tensile and bending test.

4.6.1 Mechanical properties of flax/PLA

The fibre reinforced composite materials consisting of high strength and modulus bonded to a matrix with distinct interfaces boundaries between them [232]. Therefore, it is necessary to evaluate the mechanical properties such as tensile strength and modulus, to find the link stiffness between the energy consumption of synthetic and natural composite material. Table 19 presents a primary data of the new composite materials that was obtained using random samples.

Table 19: Tensile test of natural composite flax/PLA. The primary data of the composite materials were obtained using random samples, as shown on the table. The result was used to improve the mixture of the flax and PLA fibre during the production of the flax/PLA tape fabric [Net composite].

Mechanical Property	40wt.%Flax/60wt.% PLA	50wt.%Flax/50wt.%P LA	60wt.%Flax/40wt.%P LA
Tensile strength(MPa)	57	57	88
Tensile Modulus(GPa)	109	21	131
Flexural Strength(MPa)	65	144	110
Flexural Modulus(GPa)	5	14	8.8
Resin content wt. %	50%	50%	50%
Density (g/cm ³)	1.33	1.36	1.33

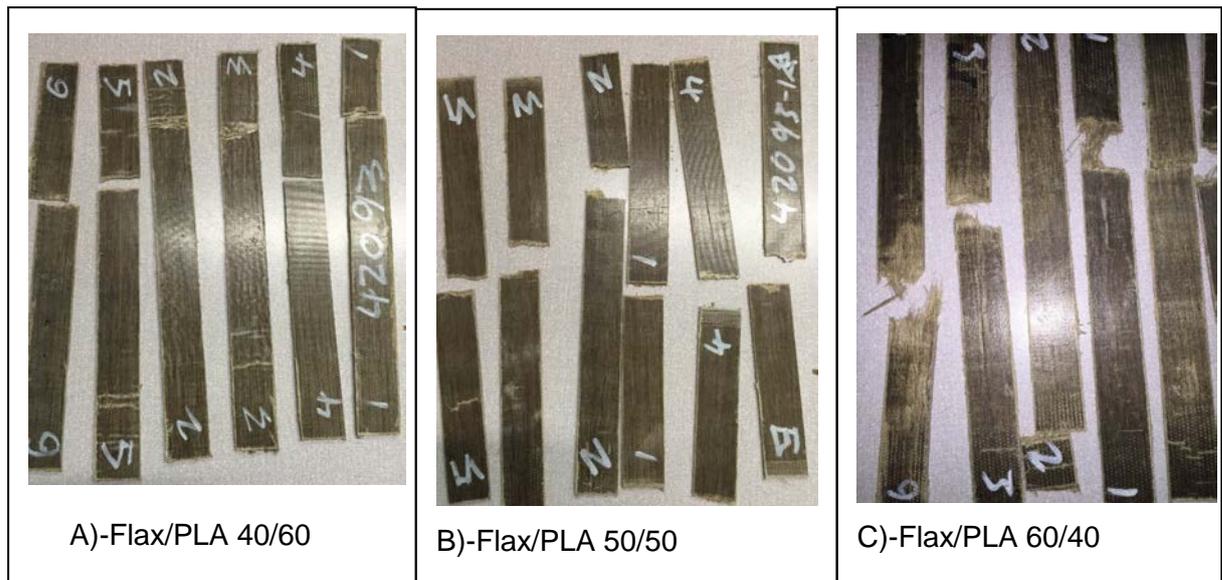


Figure 34: The tensile test of the flax/PLA tape was estimated using a tensile machine for evaluating the mechanical properties. The sample was broken at different points and data was recorded [Net composite].

Figure 34 presents different areas where the sample was broken after the tensile test. The mechanical properties of the tests vary with the fibre volume fraction percentage of flax or PLA. 50%flax / 50% PLA has a higher flexural modulus of 10 GPa follow by 60%flax/40%PLA with 8.5 GPa and 40%flax/60% PLA has the lower at around 5 GPa with flax presenting a lower mechanical property of flexural modulus overall. 50%flax/50%PLA bounced with higher flexural strength at 140 MPa follow by 60%flax/40%PLA and the last one 40% flax/60% PLA with 65 MPa. 60% flax/40% PLA has a higher tensile modulus of 18.2 GPa and tensile strength around 89 MPa followed by both 50%flax/50%PLA and 40% flax/60% PLA which has the same tensile strength of 58 MPa and slightly similar tensile moduli for around 14.8 GPa [Netcomposite]. Finally, 40/60 flax/PLA has poor properties, 60/40 flax/PLA is too dry, and 50/50 flax/PLA is somewhere between, but still not quite optimal. The graph A and B in Figure 35 shows the tensile and flexural strength and flexural and tensile modulus of different ratio of the composite flax tape.

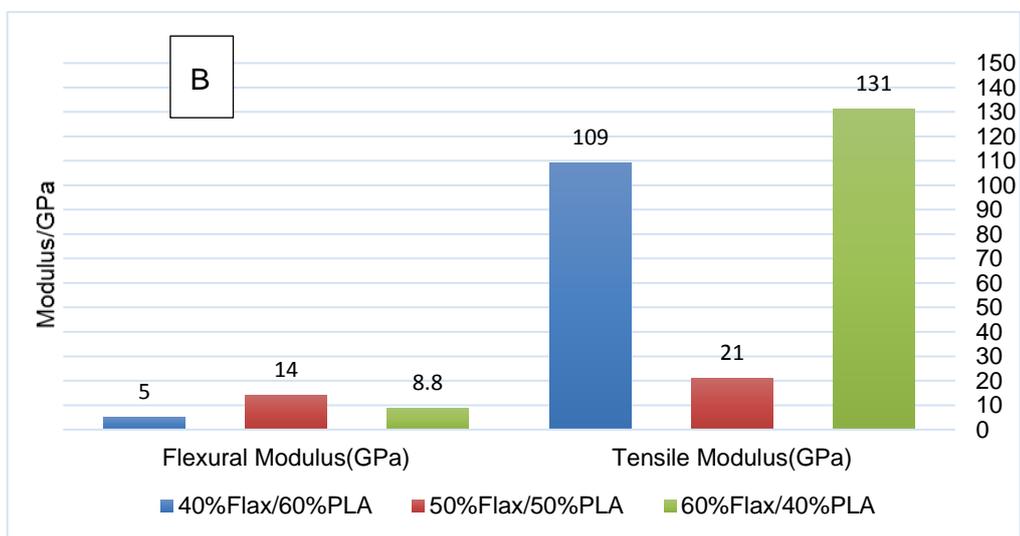
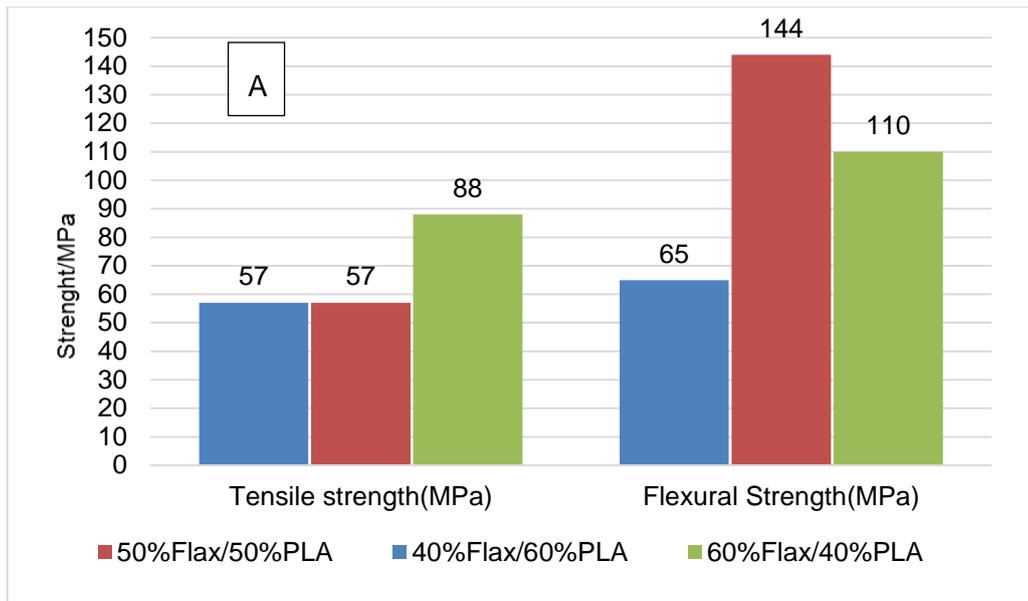


Figure 35 : Graph A and B shows the mechanical properties of natural composites flax/PLA tape. The bars chart illustrates the mechanical properties of flax/PLA tape of flexural and tensile modulus test, based on the percentage of flax and PLA fibre blended together [Netcomposite].

The range of volume fraction percentage of flax and PLA may increase or reduce with some mechanical properties such as tensile strength, flexural modulus, tensile modulus, depending on the percentage of both materials commingling together to form a composite material. The fibre volume fraction has an impact on the mechanical property; therefore, with a high flax fibre volume fraction and lower volume fraction, PLA has a higher tensile strength. A lower volume fraction of flax and high volume fraction of PLA has a high rigidity composite.

4.6.3. Mechanical property of flax/MAPP

The flax/MAPP tape was produced using the same process parameters that were similar to flax/PLA tape. The mechanical properties were evaluated using the same conditions and testing machine presented in Table 20.

Table 20: Tensile test of natural composite flax/MAPP. The mechanical properties vary based on the mixture of flax and MAPP test. This result is used to improve the manufacturing blend of the composite fibre tape [Netcomposite].

Mechanical Property	40%Flax/60%MAPP	50%Flax/50%MAPP	60%Flax/40%MAPP
Tensile strength(MPa)	102	105	105
Tensile Modulus(GPa)	12.5	13.8	12.5
Flexural Strength(MPa)	80	91	85
Flexural Modulus(GPa)	7.5	6	7.8
Resin content %by wt	50%	50%	50%
Density (g/cm ³)	1.13	1.16	1.22

The development of unidirectional (UD) flax/PLA and flax/MAPP is to enable large volume production at relatively low carbon dioxide emissions. Each process shown is followed by electricity use and CO₂ emissions. Fibre Blending is the combining of two different types of natural fibre to achieve a combination of product characteristics. For the mixing of this process, we will produce a natural fibre fabric that can be useful in the automotive industry show as door panel etc. Figure 36 represents the mechanical properties (tensile , fluxural modulus,tensile, flexural and strenght) of differents ration of the composite flax/MAPP tape.

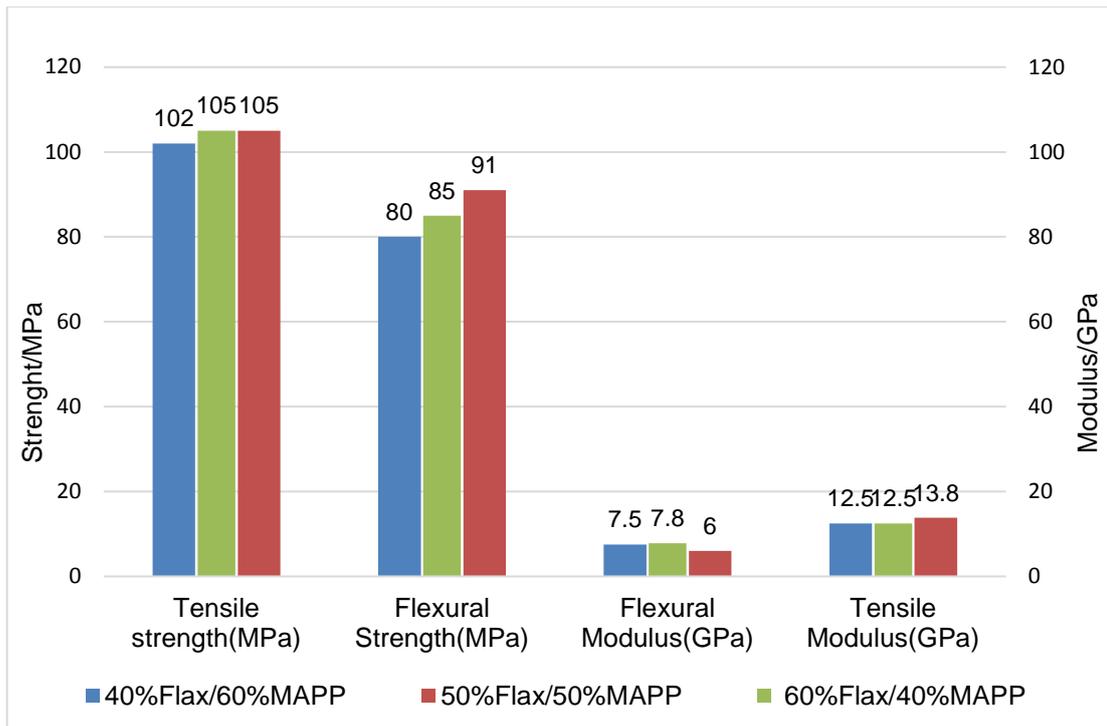


Figure 36: This shows the mechanical properties of flax/MAPP. The bars chart illustrated the mechanical properties of the composite materials flax/MAPP tape of tensile, flexural strength and modulus through the test (source: Netcomposite).

The test shows that the tensile strength is high than flexural strength follow by flexural modulus and tensile modulus. The composite material flax/MAPP tape with more percentage of flax has a high mechanical property that other such as 50% flax/50% MAPP and 60% flax/40% MAPP.

4.6.4 Thermoset laminates using vacuum infusion

The vacuum infusion process (VIP) is a technique that uses vacuum pressure to drive resin into a laminate. Dry materials are laid into the mould; the vacuum is applied before resin is achieved, the resin is sucked into the laminate via carefully placed tubing. Laminates assumed to be made by vacuum infusion using Scott Bader Crestapol 1250LV or a similar resin. The VIP was used to produce some composite material and test the materials part to find out their mechanical properties. Table 21 show the mechanical properties of laminate composite materials using Vacuum infusion technique.

Table 21: Mechanical properties of thermoset laminates vacuum infusion technique. The table showed us the composite materials content and density, as well as the modulus of the material base of the process used to manufacture the composite materials.

Mechanical Properties	90/10 flax UD tape (10% PLA binder)	Flax UD fabric from yarn	Glass UD fabric
Fibre content (% by vol)	40%	30%	50%
Fibre content (% by wt)	45%	35%	68%
Resin content (% by wt)	55%	65%	32%
Density (g/cm ³)	1.3	1.27	1.85
Modulus (GPa) UD lay-up, 0 dir	20	18	38
Modulus (GPa) 0/90 lay-up, 0 dir	11	9	19

The information on composite material flax UD tape, flax UD and Glass UD fabric was made with a resin matrix using compression moulding. All those materials have an approximately similar density. We can see that Glass UD fabric have better mechanical property that flax/PLA and flax UD. We can see that through the manufacturing process, the mechanical properties can be improved by producing hybrids of composite fabric materials.

4.6.5 Thermoplastic laminates using a press mould

There is a press moulding method for producing a multi-layer moulded parts comprising a thermoplastic resin body having a plurality of ribs or bosses on one side and a layer of a form laminated on the same side of the thermoplastic resin body having said ribs and bosses. The laminate composite materials assumed to be made by press moulding presented in Table 22.

Table 22: Mechanical properties of thermoplastic laminates composite materials. The table showed the content of the composite materials flax/PP, flax/PLA, glass/PP and the mechanical properties test of modulus of the lay-up process.

Mechanical properties	50/50 Flax/PP UD tape (50% PP matrix)	50/50 Flax/PLA UD tape (50% PLA matrix)	Flax/PP UD fabric from yarn	Glass/PP UD fabric (Twintex)
Fibre content (% by vol)	38%	45%	40%	35%
Fibre content (% by wt)	50%	50%	52%	60%
Resin content (% by wt)	50%	50%	48%	40%
Density (g/cm ³)	1.1	1.3	1.1	1.49
Modulus (GPa) UD lay-up, 0 dir	19	21	17	24
Modulus (GPa) 0/90 lay-up, 0 dir	12	14	8	12

The parameter above shows that composite materials glass/PP fabric have a higher density and modulus followed by composite tape 50/50%. The composite tape can have better mechanical properties if they have the same stiffness or weight as composite glass fibre. A comparison process has to be completed to find out the equal stiffness between the composite flax tape and composite glass/PP. We can see that most materials have different mechanical properties depending on the hybrids' composite material or single unit directional material such as glass fibre or PP. The process of manufacturing composite materials has an impact on mechanical properties.

4.6.6 Composite materials comparison

The mechanical properties of natural fibre (Flax/PLA and Flax/MAPP) was compared with other materials. The density, thickness and the higher flexural modulus were used to evaluate this comparison in Figure 37. This will help for improvement and selection the best combination for the manufacturing for natural fibre composites.

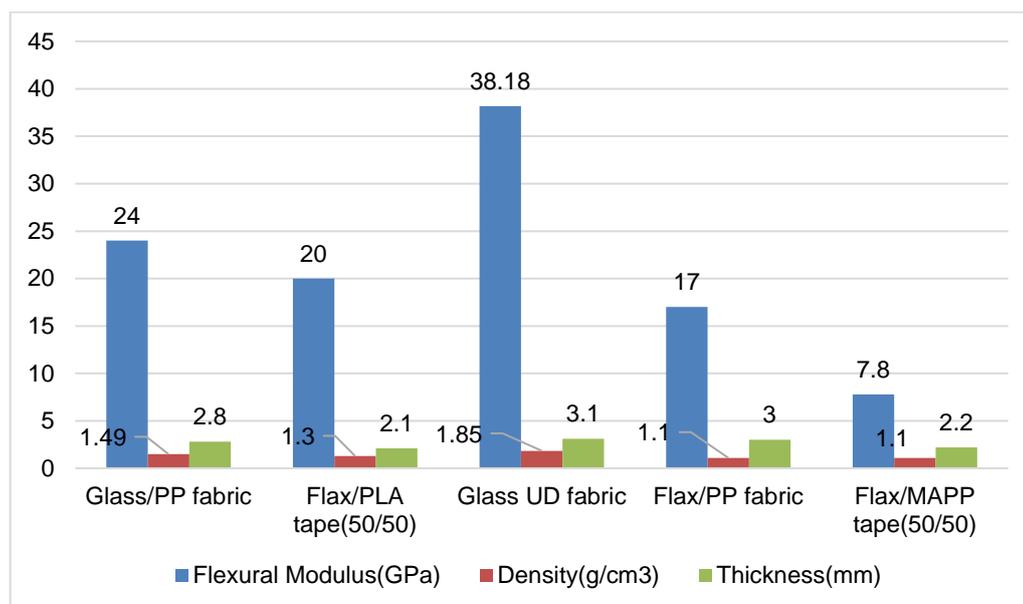


Figure 37: Mechanical propriety of composite materials. The graph illustrates different composite materials, thickness and density. We can see that glass unidirectional fabric has a higher flexural modulus and slightly higher thickness than other composite materials.

The mechanical properties of the composite material shows that glass unidirectional (UD) fabric has a high flexural modulus and density. The flax/MAPP displays a lower flexural modulus and varies between 7.8GPa to 38.18GPa. Based on this result, we can work out how to improve the flexural modulus of natural fibre to reach the same level as glass UD fabric. The density of most composite materials is almost similar. The thickness of the composite materials varies between 2.2 mm to 3.1 mm.

4.7. Conclusion

The results show that flax, PLA and MAPP commingled well as matrix material for natural fibre composite. The production of composite flax tape did not show any difficulty to produce it, and moulding into component. This process to produce flax tape composite improve compatibility that other composite materials and reduce voids during moulding process. For example, Suresh described the process of laminates GFRTTP using stacking technique, layer of glass and PP are stack on the top of each other's to form a composite materials glass/PP spray with matrix resin. On stacking, the technical process has more thickness and lower interfacial adhesion between fibre and matrix after moulding.

The production of the composite material was investigated using a combination of materials. The process was selected based on the natural fibre characteristic and mechanical properties. The blend of flax and PLA was based on the thermal properties of both materials. Therefore, it allowed both natural materials to melt at a lower temperature and form a composite flax/PLA tape fabric. The advantage is that both materials kept their mechanical properties when composite flax/PLA tape fabric same as flax/MAPP tape was produced. The triaxial glass fibre is produced by superposing each layer on the top of each other and stitching. The energy consumption of the production of triaxial glass fibre is three times more than for composite flax/PLA tape fabric. Based on the mechanical property of composite flax/PLA and flax/MAPP tape fabric, the best ratio was chosen for the production because the flexural modulus varies between 5 to 15 GPa and 6 to 7.8 GPa for both fabric materials respectively. Therefore, using a compression moulding process, we can improve the flexural modulus to reach the same flexural modulus like triaxial glass fibre fabric which is higher at 38 GPa. The next step is to find the thickness needed to be added on composite flax/PLA to produce the same flexural modulus like triaxial glass fabric. The production of fabric for composite material uses different process and machinery and therefore electricity used. Ecoinvent software was used to monitor the data during the manufacturing process of the production of composite material. Thus, sensor and device were connected on the machine tape and triaxial glass fibre machine, before batch production of both materials. The machine tape for the production of composite flax/PLA tape fabric uses less electricity that triaxial glass fibre meaning less carbon dioxide emission. SIMAPRO 8 was used to simulate the results obtained by producing a system boundary and to determine the energy consumption and environmental impact of the production through auto indication 99. The environmental impact of the composite flax/PLA is less than the environmental impact of triaxial glass fabric. The material transformation, the compression moulding and the mechanical

properties of the composites materials were evaluated to improve the manufacturing process of the composites materials for better qualities.

Appropriate directions made the LCA comparison, based on energy consumption, providing a link to stiffness or rigidity. The position is shown clearly in natural fibre composites stiffness/rigidity compared to glass fibre composites. The embodied energy analysis does not show much difference between natural fibre and glass fibre composites. The energy consumption of the material production phase are favourable for a large production scale. The mechanical properties of flax and PLA are promising .Overall mechanical properties natural fibre composites still needs to be improved compared to glass fibre composites.

Chapter 5: Discussion

The work is done on LCA, divided into different groups, materials production and compression moulding process and focusing on the natural fibre and glass fibre used to make all these processes. There is a brief explanation of electricity usage and the environmental impact of all these methods. This Chapter evaluates and analyses the results obtained in Chapter 4 and introduces a new methodology, by using data from up-to-date literature to compare the results and processes through Life Cycle Assessment using Simapro software. Based on the results obtained in Chapter 4 and the data presented in Chapter 2, the methodology of the approach was improved and implemented with Simapro 8. The method will incorporate the process used during the manufacturing phase, the use of material technology to consider energy consumption and carbon dioxide emissions with other analytical facilities to examine the natural fibre composite. The energy consumption, to produce natural and synthetic composite material with similar stiffness properties, based on the thickness using a compression moulding process, is calculated. The outcome is a simulation approach based on real data to improve the use of composite materials and to show the electricity and environmental impact during the manufacturing process.

5.1. Natural fibre / Glass fibre performance

The research, in the area of natural fibres and their composites, agree that natural fibres have some drawbacks, such as poor wettability, incompatibility with some polymeric matrices and high moisture absorption [216]. In a natural fibre reinforcement composite, the matrix plays a vital role by improving the interfacial adhesion, such as composite Flax, hemp and PLA. The key differences between natural fibre and glass fibre are low density, renewability and recyclability, better energy management, wide distribution and more.

Figure 38 indicates that there are substantial differences in the mechanical properties and cost of natural fibre compared to glass fibre extract in Chapter 2 Section 2.1 and Appendix A, Section 1.A to 3.A. The research data in Figure 38 gives us information about the natural fibre characterisation and the advantages to transform the natural fibre for industry application. Then, the production process on natural fibre varies, in characterisation, depending on the supply and growing environmental condition. For example, flax has been chosen for fibre reinforced composite for many applications in industry, such as, the design interior for automotive parts, due to its availability and environmental impact. However, necessity is a long process, and it takes time to transform raw flax fibre into flax

fabrics. Bio composite attempts to use those advantages based on the mechanical and thermal properties to develop some composite fabric materials.

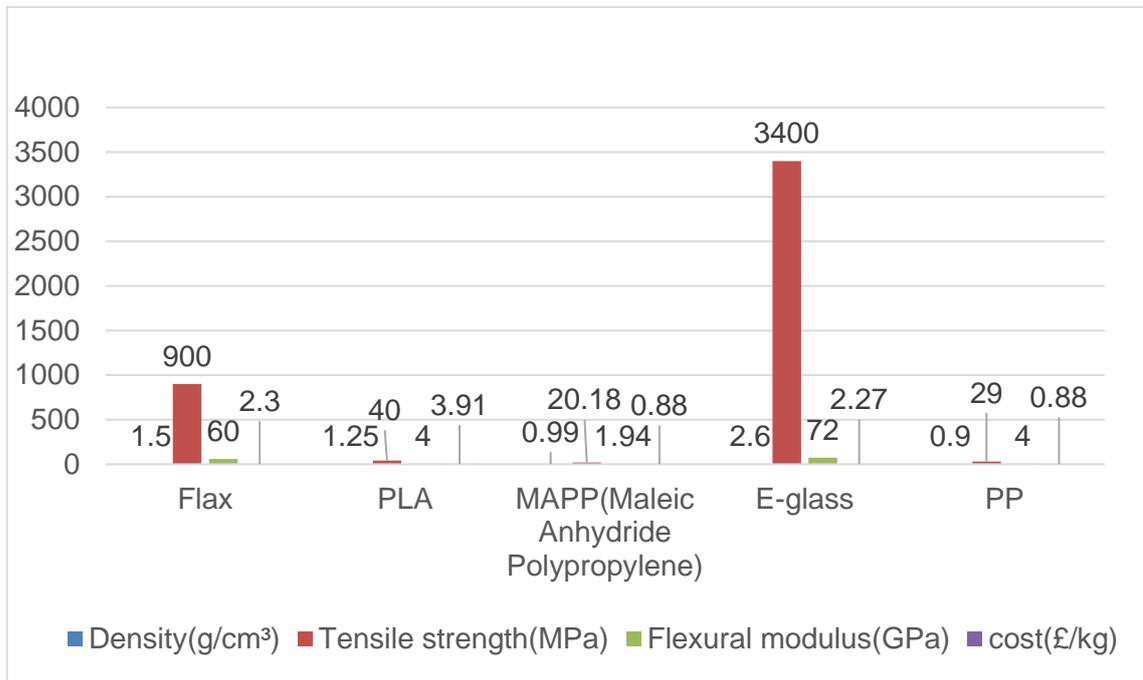


Figure 38: The graph indicates that there are substantial differences in the production and mechanical properties of the natural fibre compared to glass fibre. The density of glass fibre is higher than for PLA and flax, whereas both natural fibre have similar density and price.

The glass fibre test shows high tensile strength and lowers for natural fibre. The production of natural fibre should be higher than glass fibre because glass fibre comes from synthetic materials. Nevertheless, the process has to be improved to produce high-quality natural fibre and their transformation. There has been a remarkable advancement in science and technology to discover the low density, high strength, high stiffness to weight ratio, excellent durability, and design the flexibility of natural fibre for the industry. However, further study can show that by mixing different natural fibre, the process will improve the mechanical properties. Therefore, the manufacturing method can improve the mechanical properties of the composite materials if we fight the right combination to produce composite materials. The information about the microstructure can be retrieved from observations of fracture surfaces, which is the basis for the scientific discipline of fractographic [233]. We believe that more comprehensive fractographic studies of natural fibre composites can aid in the further development of these materials. Therefore, the microstructure of the composite flax/PLA tape had not yet observed the cross-section of

the fibre cell layers, which will necessitate the use of additional equipment and future research. Flax and PLA fibre was aligned, mixed and then laminated at a melting temperature, to form a composite flax/PLA tape. Future research can be based on the composite flax/PLA tape that possesses a number of special microstructure characteristics not seen in conventional composites. Specifically such study might shed light on the typically reported moderate strength performance of the composites, which is conflicting with the highly optimised composite and structure. This will possibly influence the mechanisms governing the properties of the composites.

5.1.1 Fibre and polymeric resin systems for composites

A composite material is known as a material having two or more chemically different phases. When the natural fibre is combined with the polymer reinforced resin/ matrix, they join together to form a composite material that possesses both their physical and mechanical properties. The continuous phase is termed as matrix and there other components mixed with it known as reinforcements or fillers. Reinforcement is added when the composite material requires a certain mechanical property that has to be achieved. The composite material achieved through this process would also be cost-effective and also satisfy the needs where other materials have been used through its improved mechanical properties.

As a result of research, it has generated biodegradable composite materials such as Anderson and Pedersen developed composite film using Polylactide and jute fibre stacking technique to form composite materials. The development in ecological composites, designed a combination using a leaf and fruit fibre in natural rubber to increase the dielectric constant of composites materials [234]. The mixture of the three natural elements did not interest industrial applications. Another development of bio composite was the preparation of composite comprising of waste paper in natural rubber along with boron carbide, which did not bring attention for future improvement [234]. In another study bio composites, were fabricated using non-woven fibre mat (90% hemp fibre with 10% thermoplastic polyester binder as reinforcement) and saturated resin as well on a blend of Unsaturated polyester fibre, which was developed to improve the thermo-mechanical properties of these composites [235]. These bio-composite materials did not introduce a robust model such as life cycle assessment during the development process of the biodegradable composite materials. The work intended to present an outline of main results based on hybrids composites focusing the attention in terms of processing, electrical mechanical properties.

We used the manufacturing process and life cycle gate-to-gate to produce natural non-woven composites materials. Based on the energy and environmental impact and their thermal-mechanical properties to combine two fibres into one. Flax, MAPP and PLA were used for a state of art techniques process to provide composite tape materials. The method and process used to develop those materials were different from the previous plan and technique used, based on the literature review on composite materials using stacking technique, layers by layers or mat process. This innovative method produces a thin and steady, continuous composite tape fabrics applicable in industry automotive and others. The introduction of life cycle assessment was to evaluate the technique during the production phase of the product and to measure the electricity and ecological impact. The results and improvement of the materials was to describe as well as to compare the prediction process and some characteristics with other articles already on the market. One of the advantages of this production is to produce lower energy consumption and ecological impact while reducing the weight of the materials by increasing performance.

5.1.2 Why use natural fibre in industry

The introduction of natural fibre composites for industrial usage brings a level of uncertainty in the design of new parts as described in Chapter 2, Section 2.1, which can be seen in Table 27. We have already stated that a composite is a mixture of two or more distinct constituents or phases. However, this definition is not sufficient, and three other criteria have to be satisfied before a material can be recognised as a composite [67]. First, both constituents have to be present in reasonable proportions, say greater than 5%. Secondly, it is when the component phases have different properties, and hence the properties of the composite are noticeably distinct from the properties of the constituents, that we have come to recognise that these materials as composites [67]. For example, in the automotive sector, natural fibre such as flax, hemp, polypropylene and wood have been incorporated into a polymer matrix which gives relatively inexpensive composite materials. It has been transformed into a composite material part for the bodywork of the Henry Ford car and the design interior for the Trabant car, i.e. door panels, and seat backs. The reason for this implication of natural fibre in the automotive industry is the potential to reduce weight and carbon dioxide emissions significantly. Another benefit of using natural fibre composite in automotive design are the claims of reducing the process of manufacturing and energy consumption by speeding up the productivity of the part [13]. The process to use natural fibre in the past differs from one method to another as shown in Figure 39, because in the past, there have not been standard methods to produce

components. The primary objectives were to use natural fibre to reduce the use of synthetic materials and weight reduction. Flax fibre was used many years ago (presented in Chapter 1, Section 2.1, and Table 1) as a composite reinforcement material to find the best compatibility and enhance the mechanical properties.

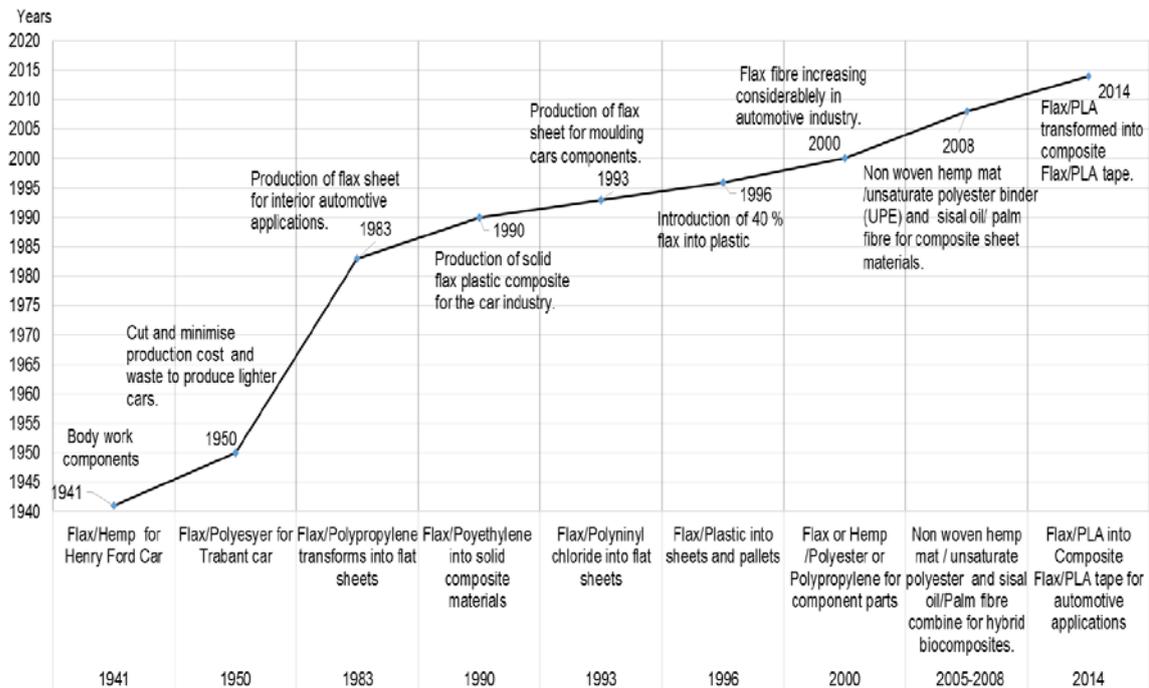


Figure 39: This graph shows the development of natural fibre composite material for industrial applications. The materials development for the car industry started in the past decade to improve the body of the car by reducing waste and weight. The natural fibre are combined to form a composite sheet or tape in recent years. This mixture of two materials in one consist improve the mechanical and thermal properties of natural fibre in industry applications.

Hybrids are usually multilayer composites with mixed fibres and are becoming common place such as flax/Hemp and flax/PP. It was shown that the presence of a coupling agent and hybridisation with composite materials fibre is a viable approach for enhancing the interface, the mechanical properties and durability of natural fibre composites. Figure 35 extract from Chapter 2, Section 2.1 from literature surveys shows significant progress of using flax fibre reinforced composite for automotive applications. Constant progress was made since 1940 until 2014 and there is continued research of manufacturing natural fibre into composites. It is necessary to determine the tensile and flexural test to investigate the mechanical properties and fibre/matrix compatibility of the natural composite materials

tape. Therefore, the mechanical properties will give us information about the quality of the natural composite material produced

The research to improve fibre reinforced composite materials for high application for the automotive industry has shown that both fibres and matrix retain their physical and chemical identities. However, the produce of a combination of properties cannot be achieved with either of the constituents acting alone. We can see that many of those fibre-reinforcement composites materials will offer a combination of strength and modulus that are either comparable to or better than many traditional metallic materials.

Composites material has been used in the automotive design for weight reduction and fuel efficiency by replacing some synthetic materials with natural fibre for the design interior of the car. Innovation has been increased to improve the manufacturing process of natural fibre and thermoplastic reinforced composites for automotive applications. Therefore, more companies like BMW, Ford and McLaren Automotive started to introduce composite materials in automotive part such as chassis, Roof and Door panel to improve the efficiency of the car and to reduce the use of steel. Therefore, it is necessary to implement life cycle assessment (LCA) to investigate the manufacturing process and environmental impact to find the hot spot of the composite materials during production.

5.2 Progress of life cycle assessment in industry

In this study, described in Chapter 1 about LCA, looks at how the energy flows throughout the lifetime of production and manufacturing of composite compared to other materials and processes. The results can be used to optimise the environmental performance of a single process to improve the environmental performance of a company. As *Jonathon Porritt in Capitalism as if the World Matters (2005) has said, in chapter 1. The difficulty to achieve to achieve theses efficiency gains is life-cycle analysis.*

While the concept of the LCA is simple, the analysis is quite complex in reality, primarily due to the difficulty in establishing the exact system boundaries, obtaining accurate data and interpreting the results correctly. Chapter 2 shows a recent improvement of LCA and how the work has been carried out and established since 2006. This started with the Coca-Cola Company, which improved its product and production performance with the environmental publication of beverage containers and the energy used to produce them. In 1972, the first handbook on the LCA assessment had been established on energy release, but the LCA standard and method has not yet been defined. In 1990 to 2006, the LCA was created through the international system organisation (ISO) and standardised (Goal, Scope, system boundary, functional unit and environment impact) and this has been made public.

A brief improvement of the LCA was founded in recent years as we can see in the graph below, which is an extract from Chapter 2, Section 2.2, and Table 2. The LCA was used by different companies to understand the real environmental impact of a product, especially in the location where it was produced. There are limited research reports on the LCA for composite material and their products. Most of the LCA was focussed on product development to improve productivity, reduce energy and waste of materials. Figure 40 presents a brief development and progress of life cycle assessment since year 1969 until 2006. Moreover, more software was developed to improve the use of LCA.

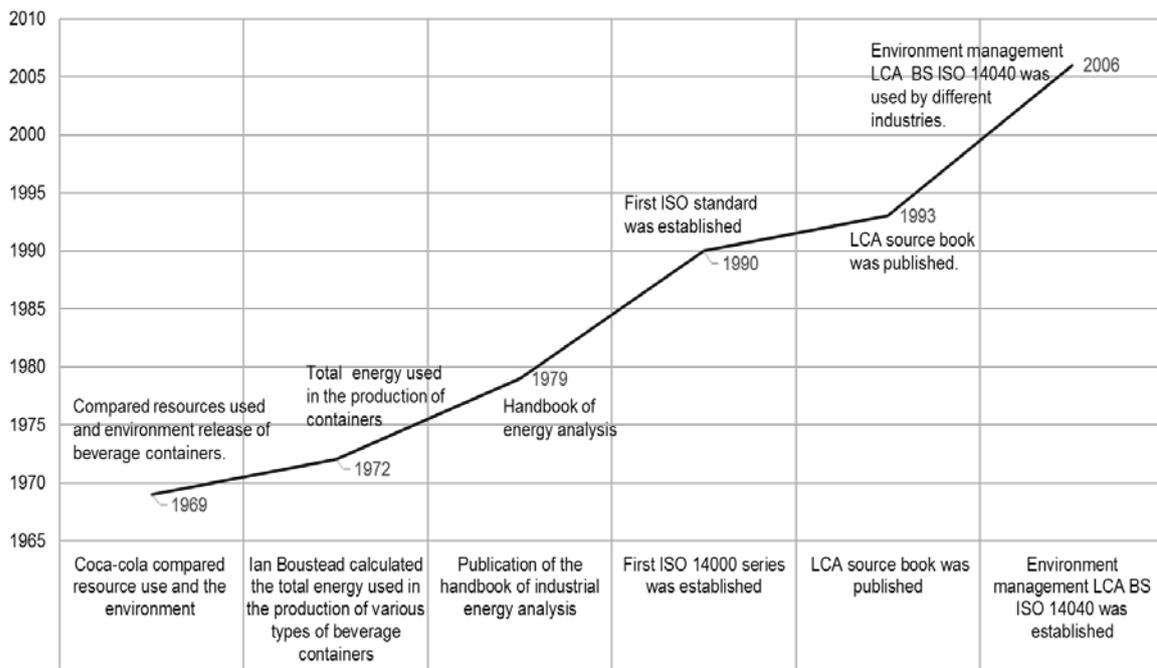


Figure 40: Development of LCA for assessing the environmental aspects and potential impacts of different products. The LCA was applied with the Coca-Cola industry and standardised through different publications and books until around 2006 [102, 103, 219].

This graph tracks the brief history of life cycle assessment through to the release of the sustainability reporting guidelines, in the early part of figure, there has been continued attention in the academic and professional accounting literature. This brief history is focused on the development of the life cycle assessment on natural fibre composite applied to the automotive industry. Finally, the LCA shows how to implement the sustainability of the accounting framework and thus, the procedure of manufacturing the product. The LCA has been used by various industries or companies to evaluate and interpret the results of their products to improve their productivity.

We have witnessed a growing interest in the integration of some materials design development, in order to achieve a more holistic approach we use the life cycle assessment framework to evaluate the process and energy base on the production of composite materials. According to some studies in chapter 1, Section 1.2 by Vink, Maureen and Joshi, by using life cycle assessment on the development of material production, we evaluate the energy consumption on the production of PLA, Flax, laminated timbers, and polypropylene. They used the assessment techniques and procedures that placed the materials at the centre of an iterative design method. However, even though the integration of life cycle assessment appears promising, it also presents some issues and so a fully satisfying approach has not been found yet.

The difficulty in applying a life cycle assessment can be a lack of collaboration with industry to collect real data. Another issue on LCA is about technology change and methods to manufacture changes and improves over the years. The use of LCA based on methodology and processes are the same because of the principles and framework, but material production may have an impact on the data collection. Therefore, the results of LCA can be used as a guideline and not for the standard method. To improve the production process and information about carbon dioxide and greenhouse gas emissions. The outcomes of the test simulation in Chapter 4 show us a combination of electricity consumption and carbon dioxide emissions. The progress was made by introducing SimaPro software 8 simulation and Ecoinvent on real data collaboration, with industry partners, to develop the process tree and the eco-friendly impact of the production. The process and method was combined together to inform the public about the manufacturing process and the environmental impact of the production of composite materials.

5.3 Implementation of SimaPro 8 LCA software

Nowadays, there are a variety of assessment methods and software which can be applied to the LCA software problem as described in Chapter 2 Session 2.3, Table 3. These methods are used to assess and analyse the primary data saved or inputted on the system such as production process, process and network tree, moulding process, energy consumption and carbon dioxide emissions presented in Figure 41. Care is needed in interpreting the results of the LCA to produce and compare products. Also, product comparisons across alternative or substitute products are meaningful only when the same methods and system boundaries were used to derive the results.

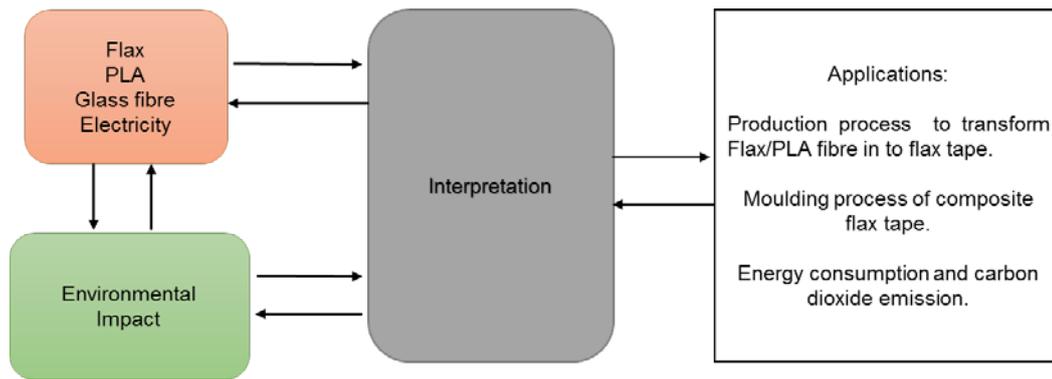


Figure 41: Life cycle assessment framework of the production of composite flax tape and carbon fibre. The LCA framework were implemented to transform flax/PLA fibre into flax/PLA tape and triaxial glass fabric. The moulding process displays the energy consumption and carbon dioxide emissions during production [118].

To explore the life cycle assessment framework, SimaPro 8, Wizard was used to simulate the manufacturing process of the production of flax/PLA tape and triaxial glass fibre production through the process tree and evaluating the impact assessment. The moulding process was simulated through the same software to produce the process tree and evaluating the environmental impact. Through the process tree, the carbon dioxide on air is produced to show the level on our environment.

Impact assessment translates the inventory data into contributions to ecological effect through the eco-indication 99 weighting categories. Here, conclusions are drawn from both the process tree and environmental impact. LCA is usually used to compare and improve both products and processes through data collection, modelling and reporting. In this study, product pairs of the same functionality are assessed. The focus of this study is on the comparison of the manufacturing of composite flax tape and their fossil-based, non-renewable counterpart, glass fibre. The primary data on the energy consumption is input on the LCA software (Simapro 8), simulation through the process tree and environment impact through eco-indication 99 weighting, excluding long term factor. This simulation through Simapro 8 software produces a process tree and carbon dioxide emissions of the electricity use and eco-indicator 99 from the environmental impact.

Therefore, we illustrate the link between the three inputs, by identifying the materials, the process and the energy consumption. Through a work practice, that could also interpret other typical applications, the simulation software was not identified in the literature reviews apply on life cycle assessment. By integrating the Simapro software, we can have many approaches on the impact of the ecological concern. The analysis of the process using Simapro eight allowed us to establish a further case study for the improvement of materials development. These are the combinations of mechanical properties and life

cycle gate to gate for the compression mouldings process. The introduction of Simapro eight for life cycle assessment has improved the evaluation of the manufacturing process and new characteristics are shown by the outcomes, through the simulation.

5.4 Evaluation of the manufacturing process of the production of triaxial glass fibre and flax/PLA tape.

The life cycle gate-to-gate is limited to material production and manufacturing on the input and output called gate to gate, to produce composite material on the tape machine and triaxial machine. The system boundary in Chapter 3, Section 3.2 and Figure 6 is limited to both machines; therefore, details of specific material and energy flows, emissions and manufacturing processes vary depending on the specific application. However, material flow, energy use, emissions, and environmental impacts overall these stages need to be modelled, inventoried and analysed for a comprehensive life cycle assessment. The system boundary and the process used to produce a triaxial glass fibre (TGF) and flax/PLA tape (FT) is shown on the figure above. The environment, aspects and potential impacts, throughout a products life from raw material production and extraction through production are not considered on this study as shown. LCA takes a comprehensive gate to gate approach thus focusing on only specific life cycle stage in material production and evaluation on the energy consumption, based on the recent series of ISO standards 14040 to 14043 provided in detailed guidelines for conducting LCA. Simapro was used to produce a process tree and deductions of the environmental impact.

5.4.1 Why produce flax/PLA tape

The manufacturing processes are to transform raw material (flax/PLA) into useful products for their potential uses in composite material, using energy and material resources. During these processes, energy is consumed and the material resources used are changed, creating a new product. The manufacturing process can have a significant consequence for the environment and sustainability, especially when these processes are practised on a large scale, for example, in Chapter 2, Section 2.1, Placket and Anderson combine Polylactide film and jute film mats to generate biodegradable composites materials. Moreover from the literature review, the hybrid non-woven flax is mixed with polypropylene mould directly into shape. Several studies in chapter 2, Section 2.3.1 have focused on estimating the energy consumption of various production processes of glass fibre, carbon fibre, flax fibre and PLA. However, most of the data is varies base of the economies scale of the region or country that produce electricity. This is due to the limitation of data

collection, it is limited primarily to the theoretical calculation of the energy consumption models for the production of some materials. The production of the composite flax/PLA tape was assessed and the model was tested based on real data from a company specialising in material production, by commingling flax and PLA or Flax and MATT. The overview of the transformation of natural materials into component necessitating different processes and methods developed in chapter 3 and 4, to monitor the manufacturing of the component parts. Therefore, the concept of energy is applied in order to test some approaches. Energy and materials are processed to produce a product presented in Figure 42.

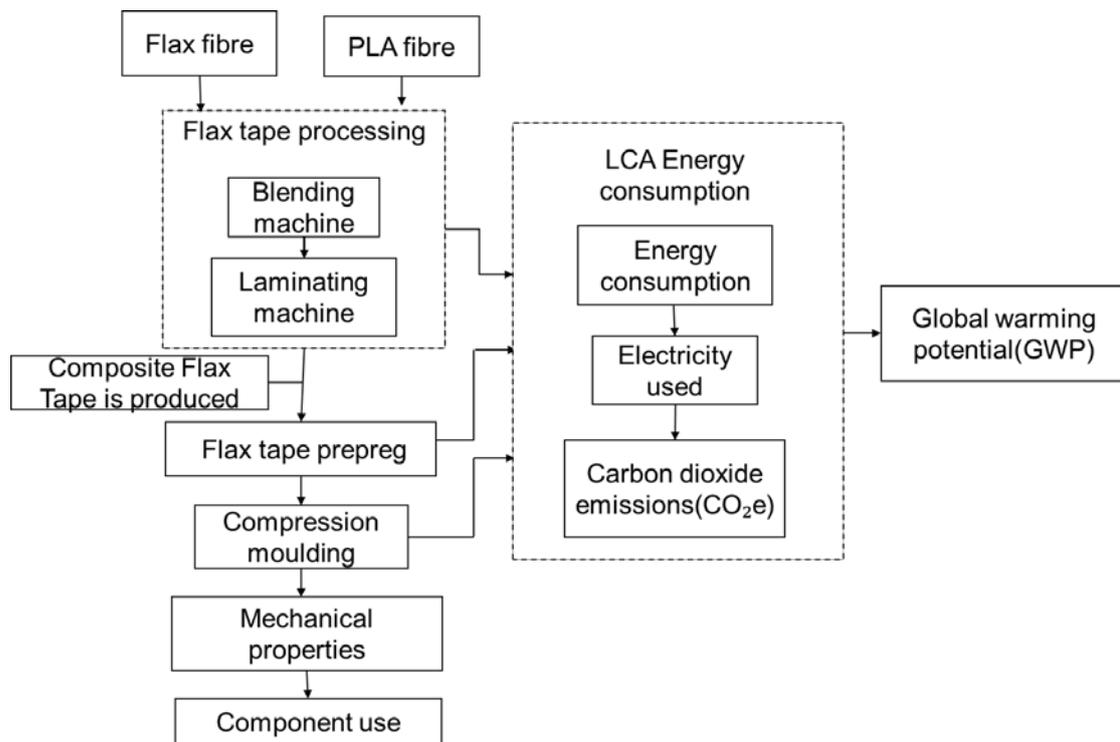


Figure 42: LCA gate-to-gate is the manufacturing process of flax/PLA tape. The flow chart shows the transformation of flax and PLA fibre into fabric and the moulding process into composite materials.

This manufacturing process of flax/PLA may have the result of reducing resource consumption, such as electricity and emissions for the manufacturing process, due to the production of the composite material on a particular machine for a single production. The life cycle assessment was the focus on the gate to gate for each process to determine the electricity use. The process will consist by fixing a device on the flax tape machine, prepreg process and also moulding process connected to a computer software elink (Ecoinvent 2.2), to extra the data of the electricity use, during production and deduction of the carbon dioxide emissions. Therefore, the energy consumption can be express as indicated in Chapter 3 based in Equation 8. And the carbon dioxide based on energy

consumption as indicated in Chapter 3 and Equation 9. A combination of equation (8) and (9) are used to calculate the energy consumption produce and carbon dioxide emissions based on the carbon footprint. After the electricity is obtained, we input the manufacturing process to produce a process tree or network process of evaluating the environmental impact. The model to develop the system boundaries assesses each step of the manufacturing system for the improvement of the composite materials. They act as a common reference point for monitoring the evolution of the product.

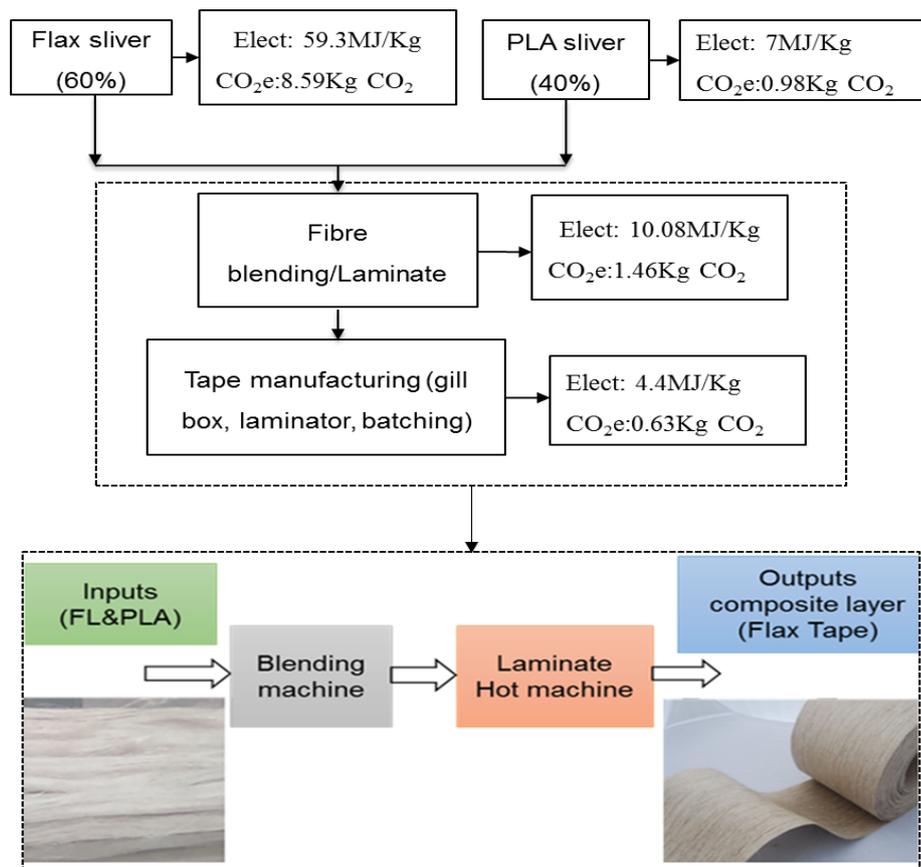


Figure 43: The gate to gate process was focused on the blended and laminated process to produce flax/PLA tape. The System boundary manufacturing processes of flax/PLA fibre is limited to the two processes that produce composite flax/PLA tape for automotive application.

The manufacturing method to commingled flax and PLA fibre to obtain flax/PLA tape. On these processes, blending and laminating at a constant speed and temperature to produce tape was evaluating. The tape machine uses purchase electricity; the daily electricity consumption is estimated at 32.54 MJ and CO₂ emissions at 4.72 kg. What the number of materials produces per year is estimated at 123.516 t/year, purchase electricity is

valued at 11877.1 MJ and producing a carbon dioxide emissions of 1362.9 kg. The concept of estimating the energy and carbon dioxide emissions is to monitor and evaluate the manufacturing process like Stiller in Chapter 2, Section 2.3.3.1, Table 6 compared and analysed the manufacturing process of glass fibre with Vetrotex Plants in Germany and Owen Corning, with an energy intensity that varies between 25 MJ/kg to 32 MJ/Kg respectively. Therefore the energy intensity varies depending on technology, methods and infrastructures.

5.4.2 Why process triaxial glass fibre fabrics

The manufacturing process of triaxial glass fibre runs at a slow speed set up to produce a good quality and smooth material with a constant thickness at 1m²/min. The average electricity obtained at each stage of the manufacturing process represents the production of the raw materials glass sand and borate into unidirectional (UD) glass. The electricity used is purchased and the CO₂e was deducted for energy consumption. The development of triaxial glass fibre, for high application in engineering, is concerned with transforming roving/yarn into fabrics uses purchased electric. The energy consumption is evaluated during the manufacturing process. The process that transforms glass fibre roving into the fabric is the same process using the same machine to produce carbon fibre fabric in formax based at wakefield on machine 5. The glass roving is passed along the rolling table inserted, stitched and woven at -45⁰, 90⁰, 45⁰ before batching operation, as depicted in the methodology in Chapter 3, Section 3.5, Figure 11. There are differences in the manufacturing process of glass fibre that was not shown in the literature and lacks data and machinery that can be used for the production of glass fabric.

The manufacturing of the raw material to obtain glass fibre filament and the weaving and to stitch to produces triaxial glass fibre. Both methods can show us the whole transformation and energy consumption of the triaxial glass fibre produce. The gate to gate focuses on the weaving and stitching section of the production of the triaxial glass fibre. The glass production used electricity or gas for each step of the transformation. The electricity consumption varies for each procedure, depending on the machine and the process. The transformation of glass fibre into triaxial fabrics, necessity some safety because of the particle of glass fibre in room production, therefore, most of the electric appliance has to be covered to avoid any spark that may cause fire during the production process. The production process was focused on the dashed line for evaluating the manufacturing process and energy consumption. The input and output are known as gate-to-gate to seek maximum energy use. Therefore, the energy consumption is estimated at 57.93 MJ/kg, for a production rate of 600 g per 1.27 m wide. Figure 44 shows an evaluation

of the production of materials and energy consumption based on the real data. Through the energy consumption we can extract the carbon dioxide emissions and work out other ecological impacts.

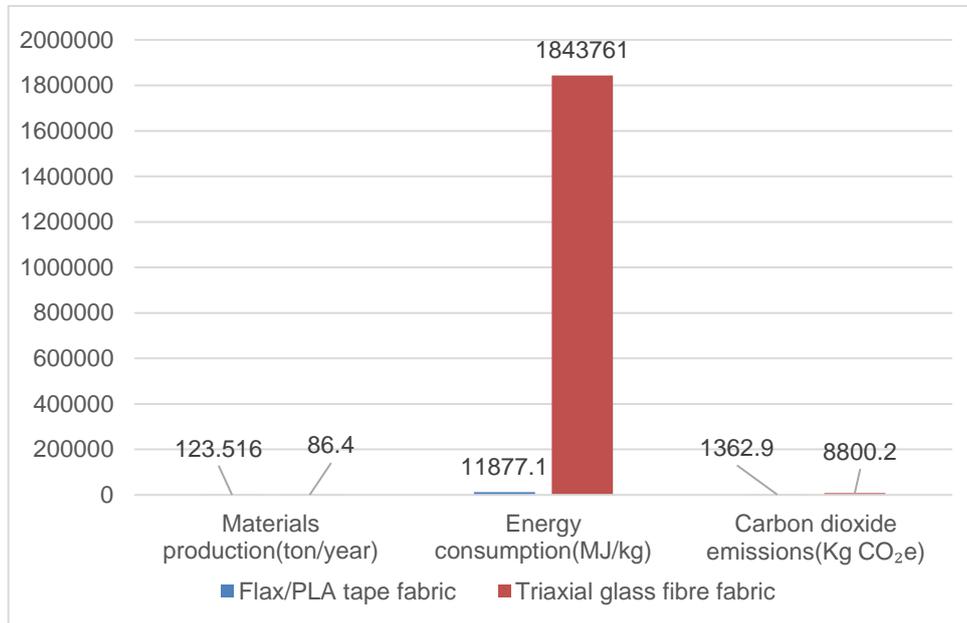


Figure 44: Materials production of flax/PLA and triaxial glass fibre fabric show that Triaxial glass fibre fabric has a higher energy consumption than composite flax/PLA tape. This can be due to different techniques to produce raw material glass fibre.

The production of triaxial glass fabric is higher than the production of flax/PLA tape. Therefore, it produces higher energy consumption and carbon dioxide emissions for triaxial glass fabric than it does for flax/PLA. The production of synthetic glass fibre is satisfied with a constant production and quality control. There are better characteristics during production and it is easy to control thickness. The production process is just an overview of the process, and can vary depending on the machine and the origin of the fibre.

5.5 Comparison on the simulation process tree

The results of the simulation in Chapter 4, Section 2.3.4, Figure 27 and 28 using Simapro software to produce the process tree, shows the energy consumption input-output data for the manufacturing process of flax/PLA tape and triaxial carbon fibre. The input energy to produce those process is 15 MJ and 58 MJ, respectively. Figure 45 shows in the red column the thermometer and the amount of carbon dioxide emissions during the manufacturing process. The life cycle assessment, shown in yellow, that both display the carbon dioxide for flax/PLA tape estimated at 0.0447 kg CO₂, and for triaxial glass fibre

fabrics are approximately 0.173 kg CO₂. Based on this, we can say that electricity is the most important inputs to produce this process tree on the LCA software simulation to obtain others result link to energy consumption.

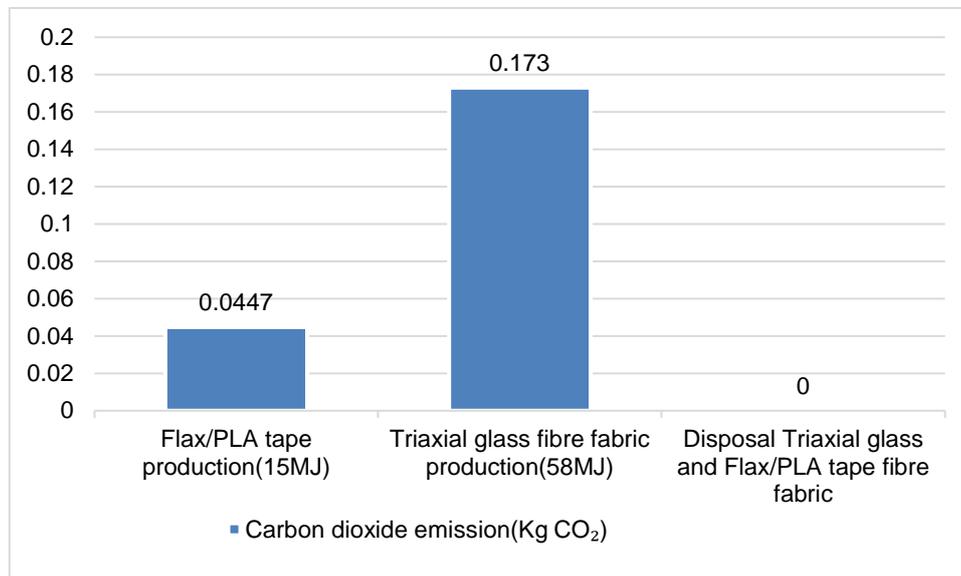


Figure 45. SIMAPRO 8 simulation process tree of flax/PLA tape and triaxial glass fibre shows the carbon dioxide. The disposal of both materials represents zero energy consumption.

This process describes the production of composite materials flax/PLA tape and triaxial glass fabric. Through the process tree, the carbon dioxide is evaluated with the weighting and eco-indication 99 to produce an analytic result. The data quality of this process is excellent, and the system boundaries of this process are from gate to gate. The overview allows us to see the difference in the environmental impact and guide for future selection of materials and processes. We can monitor data and reduce the sustainability issue of the product that we are using through different processes and inform the public.

5.6. Environmental impact of the production of flax/PLA and triaxial glass fibre fabric.

The ecological impact potential is the weighted sum of the product of individual pollutant emissions and their distinguishing factors. However, specific environmental impact potentials cannot be directly compared with others due to the different unit rates. Therefore, different environmental impact potentials should be normalised and weighted for the evaluation of the environmental impact load (EIL) for targeted products or services.

The comparison is more complicated when the origin of the materials are dissimilar, and when the production of natural and synthetic materials originate from a different process. Therefore, natural flax/PLA needs more processes and human effort than artificial fibre production. The graph provides a summary of the average impact during the production of material glass fibre and flax/PLA into the fabric. In both cases shown, there are 11 elements involved in the simulation and this varies depending on the materials to produce. The simulation shows the influence of the product during the manufacturing of composite material into the fabric.

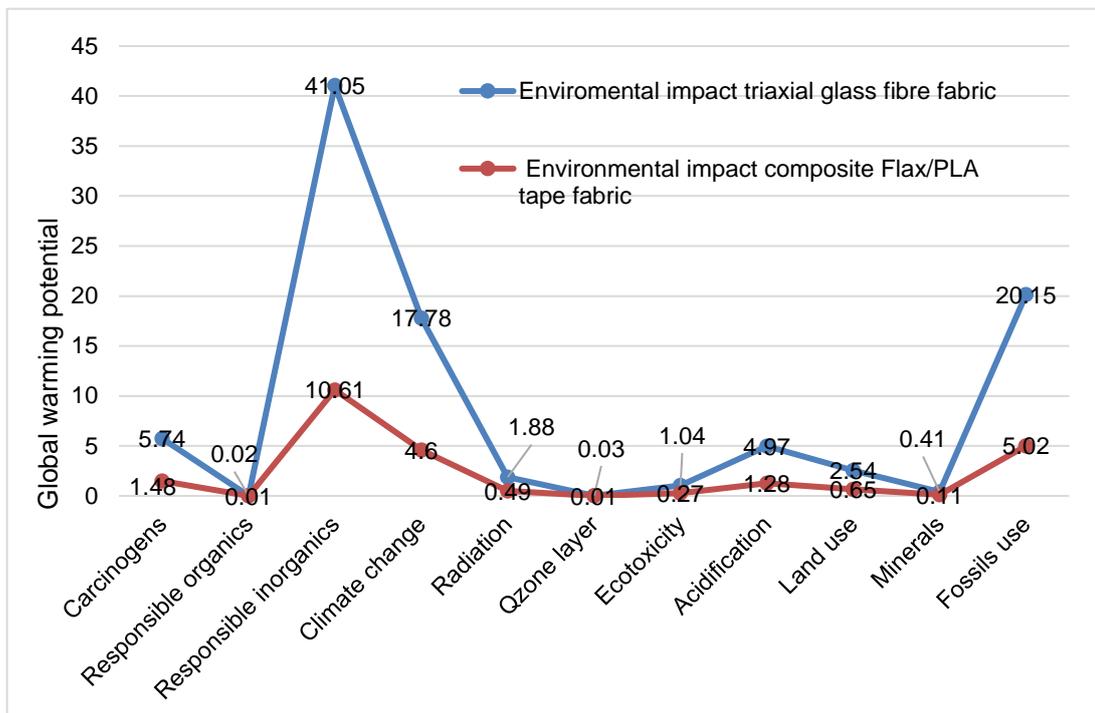


Figure 46: SimPro 8 simulation of the production of composite flax tape and triaxial glass fabric with overall environmental coverage. The responsible inorganic has a high impact on the production of materials. Whereas responsible organic has a lower impact on the materials.

The environment impact of triaxial glass fibre fabric and flax/PLA tape during production are represented in Figure 46, excluding long term emissions. The responsible ionic organic is represented and we can see that flax/PLA tape have a lower impact than triaxial glass production. Maybe this is due to the lower energy consumption as natural fibre composite during processing. For example, climate change represents 4.59 for flax/PLA tape and 17.78 for triaxial glass fabric production. The production of composite flax/PLA tape fabric shows less environmental impact than triaxial glass fabric. We can see in

Chapter 3, Section 3.3.2, Figure 7 and 8 on the manufacturing process of triaxial glass fibre that there is more necessity to control machinery whereas the natural fibre (flax/PLA) require more time and human intervention in the process. This depends on where the natural materials supply originates. Therefore, natural materials are depleting because of the irregularity of the thickness and quality of the fibre, more elements can influence the production, such as elevated temperature and speed. Further research has to be done to estimate the environmental impact for other materials for a better selection method and output.

5.7 Manufacturing process of composites glass/PP compared to composites flax/PLA tape.

The combinations or formulations of composites discussed here are mainly flax/PLA and glass/PP with the epoxy system. The manufacturing process and energy consumption were produced and compared with the literature and results. In particular, the natural fibre composites systems are flax fibres with different ratio of PLA and furan resin systems. The manufacturing processes are to transform raw material (flax/PLA tape) into useful products for their potential uses in composite material, using energy and material resources. During these processes, energy is consumed and the material resources used are changed, creating a new product. The manufacturing process can have a significant consequence for the environment and sustainability, especially when these processes are practised on a large scale, for example, the production of glass fibre. Several studies have focused on estimating the energy consumption of various production processes. However, most of the data is incomplete because it is limited primarily to the theoretical calculation of the energy consumption models for the production of composite materials.

5.7.1 Manufacturing process of composites glass/PP

The manufacturing process described in Chapter 2, Section 2.4.4 to produce GF RTP (glass/PP) composite laminates were prepared based on the film stacking technique (wet layup), using a hot compression moulding machine. The PP film and GF woven fabric were stacked one over the other for 250 x 250 x 3.5 mm thickness. The stacking sequence has four layers of GF woven fabric and five layers of PP film. The improvement of the interfacial bonding between the PP film and GF woven fabric, PP-g-MAH pellets were distributed evenly between them in all the layers with 5 wt %, 8 wt% and 10 wt% concentrations respectively. The specification can be seen in table 30. The density of the composite is easily calculated by adding up the mass of each component, i.e. the mass

of the fibre, the mass of matrix, M_m . Therefore, the mass of composite = density x volume. Further investigation can be done by looking at the cross-section area of the composite glass/PP to analyse the link between the fibre and the resin matrix. The growing fibre loading during the production of composite fabric may lead to a considerable increase in the overall mechanical properties. Xiaoyu and Chen qi peng in Chapter 1, Section 1.1 developed bamboo fibre and polypropylene and discovered the mechanical properties mainly tensile force was between 32-36 MPa. Flax/PLA is between 57 and 144 MPA based on the test results. Table 32 and Figure 43 shows a simple production method of other methodology, with the properties of the Glass/PP with coupling agent PP-g-MA. The calculation is based on the data obtained in the literature in Chapter 2, Section 2.4.4. The energy consumption of the coupling agent PP-f-MAH cannot be found in the literature. Therefore it has not been considered in the process. The forming temperature for the fabrication of the thermoplastic composite laminates was set as 190° , which is well above the melting temperature of the polymer matrix [153]. The manufacturing process to produce reinforced composite glass/PP did not include the process to produce glass woven and laminated PP film, presented in Figure 47.

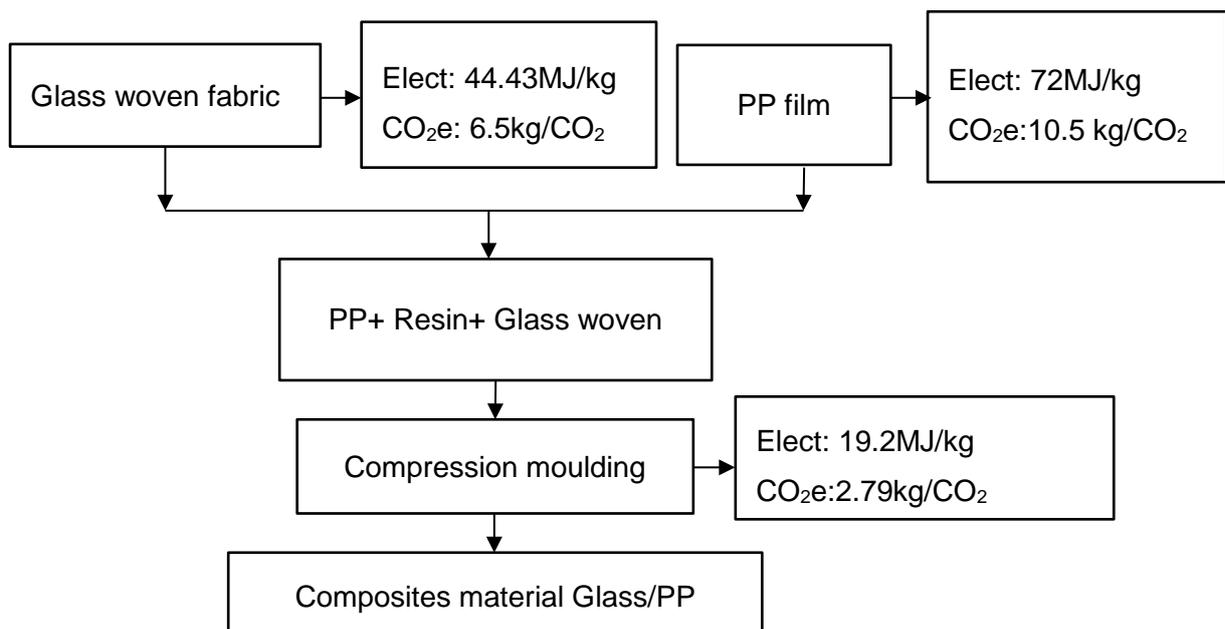


Figure 47 : The System boundary of composite moulding process Glass/PP materials. The energy consumption and carbon dioxide were evaluated at each process.

The manufacturing process of glass/PP used wet layup describe in Chapter 2, Section 2.4.1., which consists of placing the fibre on a mould surface in fabric form and impregnated them out with resin. This process is amenable to high production rates but

results in wide variations in quality. In particular, the inability to control the ratio of resin means that the mechanical properties of the laminate will vary from point-to-point and structure-to-structure [10]. The compression moulding method described in Chapter 2, Section 2.4.1 was a similar process to produce glass/PP which consisted of placing the composite materials Glass/PP in a mould cavity that is heated by hot pressure in the press. The mould is closed, the pressure is applied to force the materials together in the frame, and heat and pressure maintained until the moulded material has cured [179]. In this process, CO₂ emissions are produced, and weight loss can be estimated after the composite material part produced and the energy used for this process is around 11.8 MJ [179].

5.7.2 Manufacturing techniques of composite material flax/PLA

The results obtained in Chapter 2 and 4, from literature, gives us information on the energy consumption and CO₂ emission to produce the manufacturing process of flax/PLA as shown in Figure 44, 8 layers of flax/PLA were prepared, stacking one over the other for 1.12 mm thickness. The composite layer is placed in the mould and heating at elevated temperature 200^oc for around 30 min before applying the cooling system. The inconvenience is that some dry region occurs during the process which results in an absence of resin on some area of the composites plates. Figure 48 present some advantages of the composites flax/PLA is the regular thickness which can be commingled with other film layers for the moulding process using a strong adhesion between the fibre and matrix after the moulding process.

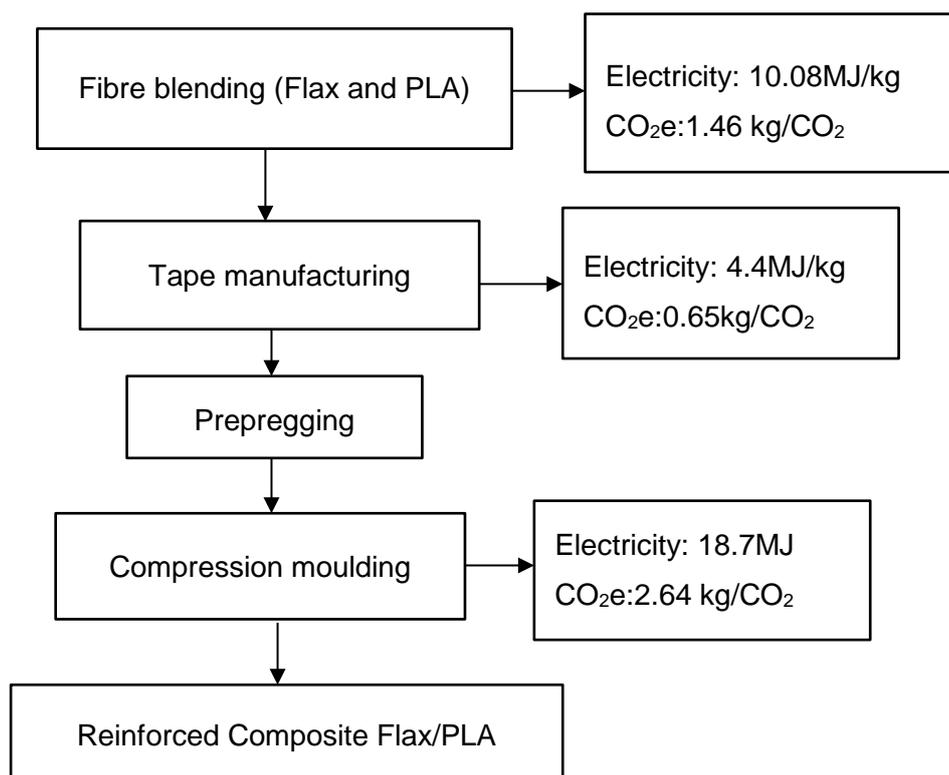


Figure 48: The System boundary of composite moulding process flax/PLA tape. The energy consumption and carbon dioxide emissions were evaluated at each process.

This method is called prepreg layup described in Chapter 2, Section 2.4.2 which consists of intermingling flax and PLA fibre in the form of flax tape by lamination. The flax tape is impregnated with a furan resin system with controlled quantities of resin before being placed in the mould. The prepreg composites flax/PLA are placed on the mould, the heat melts the resin system and allows the stack of layered tape to melt and form a solid composite material. The composite flax/PLA tape commingled has less than 1 mm thickness compared to glass woven fabrics. Due to these, prepreg techniques, often associated with sophisticated resin systems, the composite materials are cured in autoclaves under conditions of high temperature and pressure. Prepreg layup is typically used to make high-quality components for the automotive and aerospace industry. The weight loss is calculated by using the tensile modulus and the density of composite materials in Chapter 2, Equation 5. Advantages and disadvantages of the manufacturing process of composites flax/PLA and glass/PP materials can be evaluated through mechanical properties and thermal analysis. The values for porosity are from literature referenced in Chapter 2, Table 5. The composites glass with PP-g-MA resin weighted 256,53 g after moulding and weight loss of 3.78 g, whereas flax/PLA with bio-resin weigh 45.81 with a weight loss of 4.87 g. The difference in a weight loss of natural fibre over synthetic is that the natural fibre can lose water during the moulding process over the heat and forms a connection between natural fibre and resin.

We can see that some manufacturing techniques have some advantages as high-quality resin control for compression moulding (prepregging) and with some dry spot occur. Porosity can be up to 10% [176]. Whereas compression moulding (wet layup) can show a high production rate with the inability to control the ratio of resin porosity, that can be up to 25% [176]. The energy consumption was not included in the process of prepregging and wet layup. The composite manufacturing technique affects the typical achievable fibre volume fraction and porosity. For high composite mechanical properties, high fibre volume fraction and low porosity are desirable, increasing consolidation pressure realisable and typical fibre volume fraction tended to increase [176]. Porosity, an almost inevitable phase in a composite material, had significant detrimental effects on composite mechanical performance [236].

5.7.3 Gate-to Gate assessment of the energy consumption to produce glass/PP and flax/PLA

To better evaluate and compare both processes, the energy consumption in Chapter 2, Section 2.3.3 and the results in Chapter 4 to produce composite materials (flax/PLA) and Glass/PP, are produced in Table 23. Some suggested laminate data from BIOCOMP LCA calculations were included for thermoset laminates and thermoplastic laminates. The data for the prepreg process has also been introduced on the process.

The system boundary and the process used to produce triaxial glass fibre (TGF) and Flat tape are presented in Figure 47. The environmental and potential impact, throughout a products life from raw material production and extraction through production, are not considered in this study. LCA takes a comprehensive gate to gate approach thus focusing on only specific life cycle stage in material production and evaluation on the energy consumption, based on the recent series of ISO standards 14040 to 14043 provided in detailed guidelines for conducting LCA. The calculations also exclude the energy contribution of the resin and their data found in the literature. Since we cannot find any LCA data for some resin, we are using a generic polyester resin/furan resin for the base calculations where LCA data (resin energy intensity is around 4.08 MJ) might be more readily available.

As discussed, the energy of the transformation of raw material were excluded due to the limitations of LCA tools. Therefore, we were focusing just on the energy consumption of fibre in to fabrics and moulding process of the reinforced composites materials. Fibre-reinforced thermoplastic composites have to use the hot moulding process. The energy consumption for hot moulding was estimated at 18.07 MJ in Chapter 4, Section 4.1 so that we can use moulding energy intensity as an equal intensity with the hot press moulding of thermoplastic matrix composites for flax/PLA and glass fibre/PP. The energy consumption calculated in the tables is divided into 4 groups: Fibre production, Polymer resin, LCA GtG energy consumption of composites fabrics production and LCA GtG of the moulding process.

Table 23: Materials production, energy consumption and carbon dioxide emissions of the material development in to the fabric, resin and composite moulding part process gate to gate.

Materials	Energy consumption	CO ₂ e(kg/CO ₂)
Fibre production(MJ)		
PP	72	10.16
Glass roving	32	4.65
Flax	6.5	0.95
PLA	7MJ(from natural resources), 54.1MJ from fossil fuel	1.02
Polymer resin		
Furan resin	4.08	0.68
PP-g-MAH	24.4	3.52
LCA GtG energy consumption of composite fabrics production(MJ)		
PP film	72	10.16
Glass woven fabrics	58	8.18
Flax tape	14.48	2.07
LCA GtG of energy consumption for the Moulding process		
Glass/PP	19.2	2.79
Flax/PLA	18.7	2.73
Total energy for Reinforced Composites materials		
Glass/PP	128.23	18.72
Flax/PLA tape	33.18	4.85

The energy consumption of the impregnation process is not included. The higher energy consumption caused environmental impact during production. The production of flax/PLA was impregnated with furan resin, and the electricity consumption was not included in the calculation. The calculation of the composite energy consumption project aims to quantify the life cycle of composite products manufactured on the result obtained in Chapter 4. The composite flax/PLA tape was compared to the results of reinforced glass/PP from the literature surveys in Chapter 2, Section 2.4.3 and 2.4.4. It took into account materials manufactured in the form of fabrics and fibre in the form of a composite material tape. The energy consumption of the moulding process of 250 mm x 250 mm x 1.12 mm for Flax/PLA and from the literature 250 mmx250 mm x 3.5 mm into sheet reinforced composite materials were determined during the manufacturing process. The LCA assessed and generated the manufacturing process, and the energy consumption results in a unit of MJ/h. Mega-joules and kg CO₂e are the standard units of energy consumption values which present the primary energy during the product life cycle.

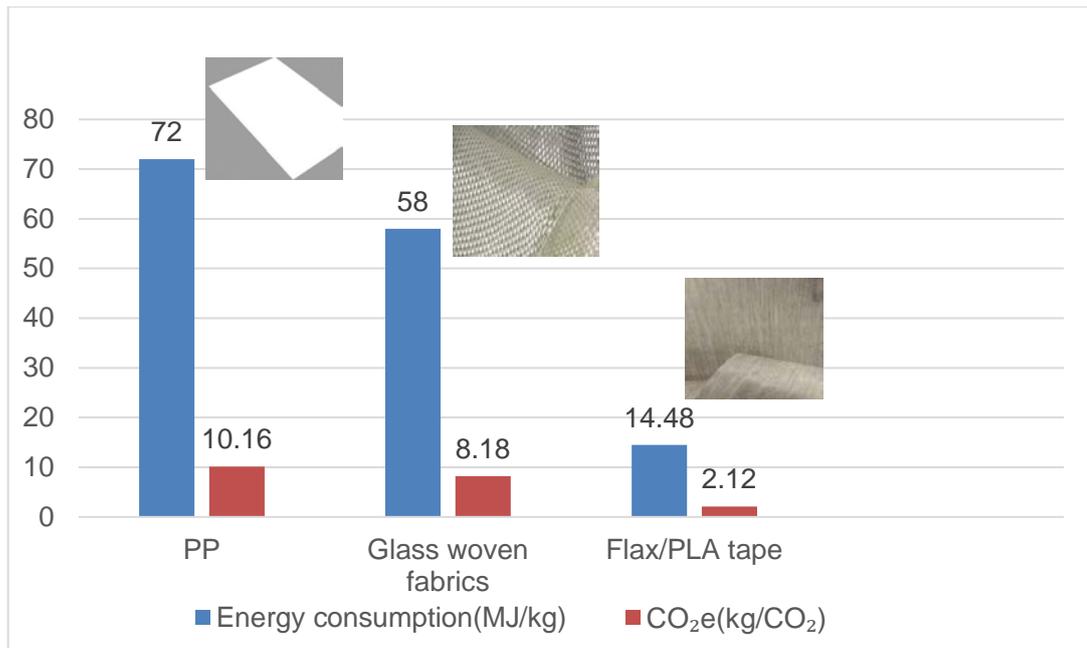


Figure 49: Electricity and carbon dioxide emissions to produce fibre for composite materials were evaluated and compared. The higher energy consumption is PP, followed by glass woven, because of the heavy manufacturing process such as process and machinery used.

The energy consumption to produce glass fibre in to glass fabrics, flax in to fibre, PLA and PP have been determined in Figure 49. The chart provides a summary of the electricity consumption of the production of materials. The synthetic materials have an elevated embody energy of 58 MJ and 72 MJ and carbon dioxide emissions 8.18 and 10.16 CO₂e (kg/CO₂) . Natural materials have a lower energy consumption of 14.48 MJ and carbon dioxide emissions are 2.12 CO₂e(kg/CO₂). The higher energy consumption of polypropylene is due to the heavy manufacturing processes such as machine use and level of performance to produce high-quality materials, with a decrease in energy consumption of glass fibre.

5.7.4 Life cycle environmental impact of moulding process

The processing techniques for the manufacturing method in Chapter 3, Section 3.7 were developed by investigating the feasibility of a multiple-step compression moulding approach for the production of flax tape, with variable ratio and fibre orientation. This manufacturing approach was proven from both formability and structural integrity viewpoints. By using an efficient system with top and bottom mould, air compressor, heat for an air compressor and vacuum pump, thermoplastic composite laminates can be multiple steps formed into three-dimensional shapes with no occurrence of visual forming

defects such as wrinkling, fibre buckling or ply folding. Furthermore, good quality bonds can be achieved between laminates that are formed and consolidated in different steps. To achieve a high degree of bonding between flax/PLA composite laminates, the consolidation process window was estimated to be 180°C for both upper and lower mould. The use of prepreg flax tape in a hot press mould was needed to improve the degree of bonding between laminate layers to avoid dry region, which led to very long production cycle times, up to 40 min per component. For future research, the maximum temperature limit of the mould press should be increased and tooling active cooling mechanisms must allow the mould to be rapidly cooled down, thereby decreasing production cycle times. With these implementations, better insight on the feasibility of the process in an industrial environment may be gained. The tree column describes the moulding process in Figure 50 of the composites material and carbon dioxide produce during production. The system boundaries of this process are from gate to gate and the energy required to produce the component.

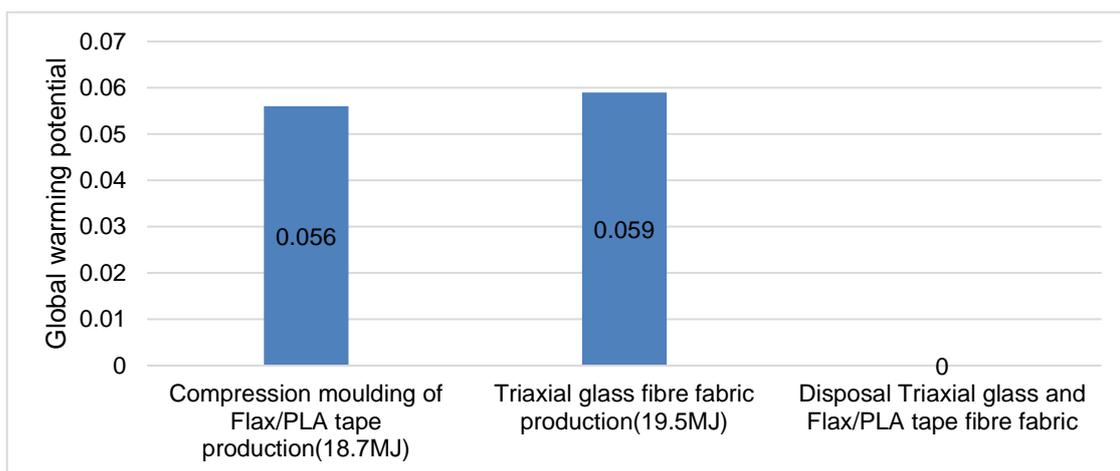


Figure 50: The cycle of a natural fibre reinforcement PLA and triaxial glass fibre (TGF) reinforced for the composite moulding process. The energy consumption is similar to carbon dioxide emissions and are approximately the same.

The total energy based on the moulding process for manufacturing a sheet of composite flax tape is estimated at 18.7 MJ and carbon dioxide at 0.0557 kg/CO₂. This is compared with higher energy estimated at 19.5 MJ and carbon dioxide at 0.0581 kgCO₂ for production of a glass/PP sheet. Therefore, the energy and emissions are considerably less to produce the composites flax/PLA tape. The natural fibres can show a great advantage of energy-saving and less environmental impact in the near future. Therefore, reducing the cost of recycling by simple degradation of the natural composite materials.

5.7.5. Environment impact assessment of the moulding process of composite fabrics.

The environmental impact in Chapter 4, Section 4.1 for the manufacture of a flat sheet of 250 mm x 250 mm for flax tape and Glass/PP with 2.1 mm to 2.3 mm thickness using the moulding process is shown in Figure 51. The total mass of each of the composite materials is estimated at 2.05 kg and 2.90 kg for flax tape and glass/PP respectively, assuming that the volume fraction of fibre is 40% flax tape and glass/PP 45% glass, and 40% PP.

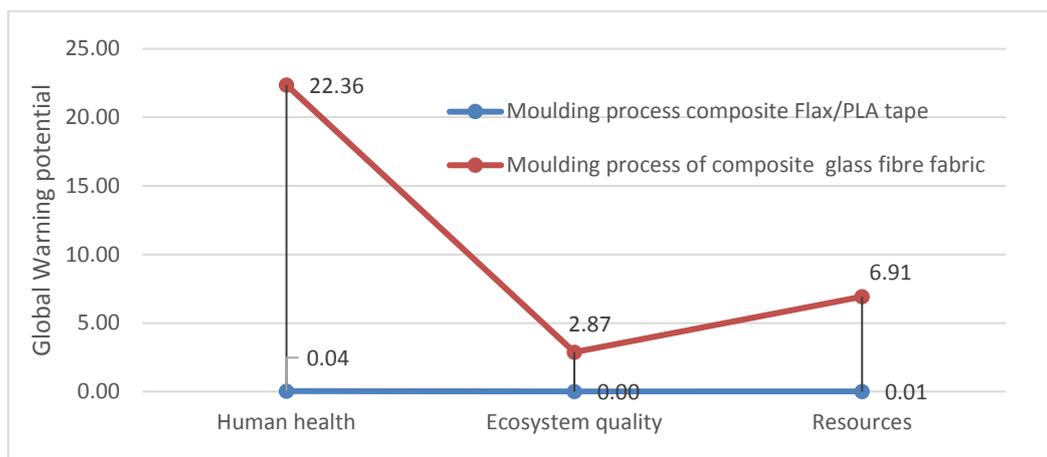


Figure 51: Environmental impact of moulding process of flax/PLA tape and triaxial glass fibre fabric. The human health of the glass fibre composite process is higher than for composite flax/PLA tape. This is due of the chemical reaction of the glass during manufacturing process linked to human health.

The graph provides the simulation process of the moulding of composite material using SimaPro software 8. We can see that the moulding process of the ecological impact of triaxial glass is overall higher than for the moulding process flax/PLA based on the three elements. Therefore, there is little human health impact, high ecosystem quality and less resources on the environment based on the eco-indicator 99 weightings, depending on the sum of materials to mould flax/PLA tape that triaxial glass fibre fabric. The production of composite material shows the different area of environmental impact depending on the type of composite material create; for example, Ecosystem quality for flax tape is lower than for triaxial glass fabric. Therefore, this is due to different manufacturing process and method to produce different composite materials. Creating a high amount of materials can have a significant impact on the environment, therefore choosing a material with lower environmental impact to provide a high amount of composite material will have less impact on the environment and during production.

5.8. Energy consumptions under equivalent rigidity between flax/PLA and glass/PP composites

Within the past three decades, considerable attention has been devoted to composite materials. Some useful equations referenced have suggested that literature has predicted microscopy stiffness (modulus/elastic modulus) of composite materials from elastic properties and volume characteristics of the constituent components. Most equations are based on the significant results obtained in the early days of research in the area of composite materials. The flexural modulus or stiffness is calculated from the initial slope of the load- deflection curve. The energy conversion based on producing equal stiffness for composite material such as glass/PP and flax/PP or flax/PLA will be governed by flexural modulus (3 point bending). The approach uses transactions between industry sectors, along with the environmental emissions data and natural resources consumption data. This determines the eco-friendly impacts throughout future supply chains with the economy.

5.8.1 Calculations methodologies

The methodology consists of using the flexural modulus of flax/PP and glass/PP under the same stiffness or providing the same composite flexural modulus (three- point bending): The flexural modulus in Chapter 3, Section 3.6.2 Equation 10, can be express as $E_{(Flax/PLA)}$ and $E_{(GF/PP)}$.

The flexural modulus $E_{(flax/PLA)}$ using equation 10 can be express as:

Equation 11: Flexural modulus $E_{(flax/PLA)}$

$$E_{(flax/PLA)} = \frac{1}{4} \cdot \frac{L^3}{wh_{flax/PLA}^3} \cdot \frac{\Delta F}{\Delta \delta} \quad (11)$$

And the flexural modulus $E_{(glass/PP)}$ using equation 10 can be express as:

Equation 12: Flexural modulus $E_{(GF/PP)}$

$$E_{(GF/PP)} = \frac{1}{4} \cdot \frac{L^3}{wh_{GF/PP}^3} \cdot \frac{\Delta F}{\Delta \delta} \quad (12)$$

Where $h_{flax/PLA}$ and $h_{GF/PP}$ represent the thickness (mm) of the composite material, w is the sample width (mm), (L) is the length (mm), $(\Delta F) / (\Delta \delta)$ represent the force to apply and

deflection. Deductions of Extra- thickness ($h_{\text{flax/PLA}}$) using E (Flax/PLA) and E (GF/PP), based on Equation 10 to produce required flexural properties while other perimeters kept the same.

Equation 13: Extra thickness to add on the previous thickness

$$h_{\frac{\text{Flax}}{\text{PLA}}} = h_{\text{GF/PP}} \cdot \left(\frac{E_{\text{GF/PP}}}{E_{\text{flax/PLA}}} \right)^{\frac{1}{3}} \quad (13)$$

Where $h_{\frac{\text{flax}}{\text{PLA}}}$ is the new thickness to determine and add on the previous thickness, E (flax/PLA) and E (GF/PP) are the flexural modulus of the composite, $h_{\text{GF/PP}}$ is the thickness of the composite (GF/PP). It is significant to determine the weight of the material that we need to add on the previous material, to determine the total weight and embody energy need to produce the new composite material. The weight of flax/PP or flax/PLA composite with known Density of composites:

Equation 14: Density of composite material

$$D_{\text{Flax/PLA}} = \frac{W_{\text{flax/PLA}}}{h_{\frac{\text{Flax}}{\text{PLA}}} \cdot S} \quad (14)$$

Where D (Flax/PLA) is the density of composite, $W_{\text{flax/PLA}}$ is the weight of the composite material, $h_{\frac{\text{flax}}{\text{PLA}}}$ is the thickness, If we assume $S = 1 \text{ m}^2$.

The density (D (flax/PLA) = D (GL/PP)) is very similar since pure glass fibre and flax fibre theoretically modulus is very similar, the extra weight required to produce similar flexural property, can be express as:

Equation 15: weight of the composite material

$$W_{\frac{\text{flax}}{\text{PLA}} = \frac{\text{GF}}{\text{PP}}} = D_{\text{flax/PLA}} \cdot h_{\text{flax/PP}} \cdot S \quad (15)$$

Therefore, in order to realize the equal rigidity (flexural modulus) of glass fibre composites, the $W_{\frac{\text{flax}}{\text{PLA}} = \frac{\text{GF}}{\text{PP}}}$ will be able to produce the flexural modulus of $E_{\text{flax/PLA}}$. $W_{\text{flax/PLA}}$ is the weight of the Flax/PLA composite that has the same thickness as the GF/PP. $h_{\text{flax/PLA}} = h_{\text{GF/PP}}$ will have to add the extra thickness that requires the new thickness for producing

an equivalent flexural modulus $E_{GF/PP}$ of $E_{flax/PLA}$ with initial thickness.

5.9. The energy consumption required to produce the new composites material.

Producing and using electricity more efficiently reduces both the amount of energy or fuel needed to generate electricity and the number of greenhouse gases and other air pollution emitted as a result. The electricity required to produce new composite materials can be determined based on some element such as moulding cycle time, density, the thickness of the composite and thermal diffusivity of the materials.

5.9.1. Moulding cycle time

The time required to produce new composite materials using the moulding cycle time. Based on the compression moulding on Chapter 2 Equation 2, the moulding cycle time (t_0) suggest by Lovejoy, the cycle time can be simplified as:

$$t_0 = \frac{h^2 \max}{\alpha} \quad (2)$$

Where α represent the thermal diffusivity of material and h is the maximum thickness of composite materials. The maximum thickness require to produce the new composite material is equal to the previous thickness and the new thickness can be express as maximum thickness ($h \max$):

Equation 16: Total thickness (h_{total})

$$h_{total} = (h_{flax/PLA} + h_{newflax/PLA}) \quad (16)$$

Where h_{total} is the total thickness, $h_{flax/PLA}$ represent the previous thickness, $h_{newflax/PLA}$ is the new thickness. The total thickness of the composites has been introduced to obtain the approximate maximum time that will allow moulding of the composite material. When the new thickness is added on to the previous thickness required to produce the same flexural properties therefore the overall mechanical properties will be improved. Following Equation 10 developed in Chapter 3 Section 3.6.2, and Equation 2 moulding cycle time (t_0) Chapter 2, Section 2.6, and the energy is time multiplied by power, therefore, the energy required to produce comparable flexural

properties similar to glass composite can be expressed as:

Equation 17: Energy required to produce additional thickness

$$\text{Energy} \frac{Fl}{PP} = \frac{h^2 \text{total}}{\alpha} \times P \quad (17)$$

Where P is the Power (kW), $h^2 \text{total}$ is the total thickness (mm), α is the thermal diffusivity. The following Equation 17 to obtain energy required to produce the new composite material is represented by the cycle time multiply by the power in kW. This can be expressed a:

Equation 18: Deduction of equation 17 to produce the energy required

$$\text{Energy} \frac{\text{flax}}{\text{PLA}} = \frac{(h_{\text{flax/PP}} + h_{\text{newflax/PP}})^2}{\alpha} \times P \quad (18)$$

Assuming that the power (kW) can be identified on the moulding machine specification, and can be expressed as $P=VI=I^2R$ [237].

Based on the heat transfer analysis, thermal diffusivity is the thermal conductivity divided by the density and specific heat capacity at constant pressure. Then we introduce the thermal diffusivity α [238]. In term of quantity and unit, measurement is expressed in Chapter 2, Section 2.4.4 Table 6. The thermal diffusivity can be expressed in term of dimension as followed [238] :

Equation 19: Thermal diffusivity

$$\alpha = \frac{K}{\rho C_p} = \frac{l^2}{t} \quad (19)$$

Where k is the thermal conductivity, density (in kg/m^3) and the specific heat referred to mass (in J/kg k). The dimensions are expressed as similar units of measurement for the thermal diffusivity (α) m^2/s , l is the dimensions of the material and t is the time(s) [226].

By introducing the thermal diffusivity, the overall energy required to produce the composite material can be expressed as:

Equation 20: The simplified equation derive from equation 18 and 19

$$\text{Energy} \frac{\text{flax}}{\text{PLA}} = \frac{(h_{\text{flax/PP}} + h_{\text{newflax/PP}})^2 t}{l^2} \times P \quad (20)$$

The energy required to produce the new thickness composite materials is expressed in kW/h. On this formula, we have the cycle time, which is the maximum thickness divided by the thermal diffusivity and the power that represents the voltage and current needed to produce energy in kW. To obtain the energy needed to produce composite materials, we calculate the time, which is the cycle time multiply by the power in kW. R (Required) if we select $h_{\text{GF/PP}} = 2.8 \text{ mm}$, $S = 1\text{m}^2$ and Table 19 give us information about the density of flax/PLA= 1.1 g/cm^3 . In these cases, we simplified the equation because of lack of data. We used the second equation for the thermal diffusivity to carry on the prediction of the energy consumption based on dimensions and time for the materials.

5.9.2 Energy intensity to generate same stiffness or rigidity

To calculate the energy required to produce the Flax/PP: this will compare flax/PLA, flax/MAPP and GF/PP against glass unit directional (glass UD) fabric that generated an equivalent stiffness or rigidity. The table shows additional information to calculate the energy needed to produce composite material based on flexural modulus. This method will allow us to predict the energy required to produce a composite material that has the same flexural modulus like any other material already on the market. By using natural material, we can improve the mechanical property of the natural composite material through this process and reduce carbon footprint emissions. The data on the table was taken from experimental results and from the literature for the prediction of the thickness need to produce the same flexural modulus.

5.9.2.1. Case 1: Flax/PLA tape thickness and energy require to produce similar to glass/PP

The calculation of the thickness to increase on the composite materials to reach the same thickness similar to other materials was predicted in different cases (Table 24). The energy conversion, based on an equal stiffness, will be governed by flexural modulus of equation 8. Flexural Modulus calculation of natural material such as flax/PP and glass/PP will be needed under a rule of two materials to produce a same stiffness, which means providing the same composite flexural modulus (based on 3 point bending).

Table 24: Thickness for increasing the flax/PLA tape and energy needed to produce this thickness is shown on the table below. The thickness is added on to the flax/PLA tape fabrics to reach equal modulus or stiffness like glass/PP. The table below calculates the energy required to produce equal flexural modulus with other materials.

Materials	Flax/PLA tape	Glass/PP	comments
Flexural modulus(GPa)	20GPa	24GPa	The result obtained from Chapter 4 Figure 46
Thickness (h1) mm Dimension is 250mm x 250mm.	2.1mm	2.8mm	Thickness of the composite materials results Chapter 4. Direct measurement of the thickness
Energy consumption	18.7 MJ/h	19.2MJ/h	
Extra thickness (h2) $\frac{h_{Flax}^{Flax}}{PLA^2} = h_{GF/PP} \cdot \left(\frac{E_{glass\ UD\ fabric}}{E_{flax/PP}} \right)^{\frac{1}{3}}$	$2.8 \cdot \left(\frac{24}{20} \right)^{\frac{1}{3}} = 2.9mm$	//	Extra thickness required to add on the h1 thickness.
Total thickness: $h_{Flax/PLA} = h1 + h2$ $h_{Flax/PLA} = 2.1 + 2.9$	5mm	//	New thickness to produce the same flexural modulus
Assuming maximum Power (KW) is 8 KW equivalent to 28.8 MJ	Assuming power is 28.8MJ	Assuming power is 28.8MJ	Power of the compression moulding machine.
Energy is time(s) multiply by the power of the moulding machine. Assuming for 1 hour. $\text{Energy}_{\frac{flax}{PLA}} = \frac{(h_{Flax/PP} + h_{newFlax/PP})^2 t}{l^2} XP$	$\frac{(5)^2 \times 3600}{(250)^2} \times 28.8$ 42MJ/h		New energy required to produce the required thickness that will have the same flexural modulus similar to glass/PP.

The thickness required to produce the same flexural modulus like Glass/PP is 5 mm and the energy consumption for moulding is approximately 42 MJ/h. This shows that the thickness and energy consumption have improved considerably.

5.9.2.2 Case 2: Flax/MAPP tape thickness and energy required to produce a similar flexural modulus comparable to glass unit directional (glass UD) fabric.

We know in Figure 26 flexural modulus of flax/MAPP is 7.8 GP and Glass UD fabrics are 38.18 GP. Table 25 present the energy required to produce the same flexural modulus similar to Glass UD fibre.

Table 25. Thickness for increasing the flax/MAPP tape and energy needed to produce this thickness is shown in the table. The thickness is added on to the flax/MAPP tape fabrics to reach equal modulus or stiffness like glass UD.

Materials	Flax/MAPP	Glass UD fibre	Comments
Flexural modulus(GPa)	7.8GPa	38.18GPa	
Thickness(h1)mm Dimension is 250mm x 250mm.	2.1mm	3.5 mm	Thickness of the existing composite materials
Energy consumption	18.7MJ/h	19.2MJ/h	
Extra thickness (h2) $h_{\frac{\text{Flax}}{\text{MAPP}}^2} = h_{\text{GL UD}} \cdot \left(\frac{\text{Glass UD}}{E_{\text{Flax/MAPP}}} \right)^{\frac{1}{3}}$	$3.8 \left(\frac{38.18}{7.8} \right)^{\frac{1}{3}} = 5.3\text{mm}$	//	Extra thickness required to add on the h1.
Total thickness: $h_{\text{flax/MAPP}} = h_1 + h_2$ $h_{\text{Flax/MAPP}} = 2.1 + 5.3$	7.4 mm		New thickness required to produce the same flexural modulus like glass/PP
Assuming maximum Power(KW) is 8KW equivalent to 28.8 MJ	Assuming power is 28.8MJ	Assuming power is 28.8MJ	Power of the compression moulding machine remaining the same throughout the process.
Assuming for 1 hour. Energy $\frac{\text{flax}}{\text{MATT}}$ $= \frac{(h_{\text{flax/MAPP}} + h_{\text{newflax/MAPP}})^2 t}{l^2} XP$	$\frac{(7.4)^2 \times 3600}{(250)^2} \times 28.8$ $= 90.84\text{MJ/h}$		The dimensions remain the same as flax/PLA.

The thickness required to produce the same flexural modulus like glass UD fibre is 7.4 mm and the energy consumption for moulding is approximately 90.84 MJ/h to produce flax/MAPP. This shows that the thickness and energy consumption have improved considerably. The energy consumption of flax/MAPP is not different from flax/PLA because the lower density of MAPP is approximately (0.9 g/mm g) and PLA is 1.24 g/mm.

5.9.2.3 Case 3: Energy required to produce the same flexural modulus like glass unit directional (glass UD) fabric using flax/PLA

Most parameters remained the same for the moulding machine and thickness for the flax/PLA. Table 26 gives us information to use flax/PLA and increase thickness to have the same flexural modulus as glass UD fabrics.

Table 26. Thickness for increasing the flax/PLA tape and energy needed to produce this thickness is shown on the table below. The thickness is added on to the flax/PLA tape fabrics to reach equal modulus or stiffness like glass UD fabrics.

Materials	Flax/PLA tape	Glass UD fabrics	comments
Flexural modulus(GPa)	20GPa	38.18GPa	The result obtained from Chapter 4 Figure 46
Thickness (h1)	2.1mm	3.5 mm	Thickness of the composite materials.
Extra thickness (h2) $h_{\frac{\text{Flax}}{\text{PLA}}} = h_{\text{GL UD}} \cdot \left(\frac{E_{\text{Glass UD}}}{E_{\text{Flax/PLA}}} \right)^{\frac{1}{3}}$	4.3mm	//	Extra thickness required to add on the h1.
Total thickness ($h_{\text{flax/PLA}} = h_1 + h_2$) $h_{\text{Flax/PLA}} = 2.1 + 4.3$	6.4mm	//	New thickness needed to produce equivalent flexural modulus.
Assuming maximum Power(KW) is 8KW equivalent to 28.8 MJ	Assuming power is 28.8MJ	Assuming power is 28.8MJ	Power of the compression moulding machine remaining the same throughout the process.
Energy is the time(s) multiplied by the power of the moulding machine. Assuming for 1 hour. Energy $\frac{\text{flax}}{\text{PLA}}$ $= \frac{(h_{\text{flax/PLA}} + h_{\text{newflax/PLA}})^2 t}{l^2} \times P$	$\frac{(6.4)^2 \times 3600}{(250)^2} \times 28.8$ =67.95 MJ/h		Energy required to produce the total thickness of the composite flax/MAPP tape.

The thickness required to produce the same flexural modulus like glass UD fibre is 6.4 mm and the energy consumption for moulding is approximately 67.95 MJ/h to produce flax/PLA.

5.9.2.4. Case 4: The energy required to produce the same flexural modulus as glass UD fabrics.

Energy required to produce same flexural rigidity same as composite Glass UD fabrics using flax/MAPP.

Table 27. Thickness for increasing the flax/MATT tape and energy needed to produce this thickness is shown on the table below. The thickness is added on to the flax/MATT tape fabrics to reach equal modulus or stiffness like glass UD fabrics.

Materials	Flax/MAPP tape	Glass UD fabrics	comments
Flexural modulus(GPa)	7.8GPa	38.18GPa	The result obtained from Chapter 4 Figure 46
Thickness (h1)	2.1mm	3.5 mm	Thickness of the composite materials.
Extra thickness (h2) $h_{\frac{\text{Flax}}{\text{MAPP}}} = h_{\text{GL UD}} \cdot \left(\frac{\text{Glass UD}}{E_{\text{flax/MAPP}}} \right)^{\frac{1}{3}}$	6mm	//	Extra thickness required to add on the h1.
Total thickness (h _{flax/MAPP})=h1+h2 h _{Flax/MAPP} = 2.1+6	8.1mm	//	New thickness needed to produce equivalent flexural modulus.
Assuming maximum Power(KW) is 8KW equivalent to 28.8 MJ	Assuming power is 28.8MJ	Assuming power is 28.8MJ	Power of the compression moulding machine remaining the same throughout the process.
Energy is the time(s) multiplied by the power of the moulding machine. Assuming for 1 hour. $\text{Energy}_{\frac{\text{flax}}{\text{MAPP}}} = \frac{(h_{\text{flax/MAPP}} + h_{\text{newflax/MAPP}})^2 t}{l^2} X P$	$\frac{(8.1)^2 X 3600}{(250)^2} X 28.8$ =108.8MJ/h	//	Energy required to produce the total thickness of the composite flax/MAPP tape.

The prediction of the energy consumption used for moulding process to produce the same flexural modulus as glass UD fabric. The thickness required to produce the same flexural modulus like glass UD fibre is 8.1 mm and the energy consumption for moulding is approximately 108.8 MJ/h to produce flax/MAPP.

5.9.2.5. Case 5: The energy required to produce the same flexural modulus similar to glass unit directional (glass UD) fabrics.

Energy required to produce glass/PP similar flexural rigidity as composite Glass UD fabrics. The table 28 gives us information to use glass UD fabric and increasing thicknesses to have the same flexural modulus that is similar to glass/PP fabrics.

Table 28: Thickness for increasing the glass/PP fabrics and energy needed to produce this thickness is shown on the table below. The thickness is added on to the glass/PP fabrics to reach equal modulus or stiffness like glass unit directional (glass UD) fabrics.

Materials	Glass/PP fabrics	Glass UD fabrics	comments
Flexural modulus(GPa)	24GPa	38.18GPa	The result obtained from Chapter 4 Figure 46
Thickness(h1)	2.8mm	3.1mm	Thickness of the composite materials.
Extra thickness (h2) $h_{\frac{Flax}{GI/PP}^2} = h_{GL UD} \cdot \left(\frac{E_{GL UD}}{E_{GL/PP}} \right)^{\frac{1}{3}}$	3.6mm		Extra thickness required to add on the h1.
Total thickness (h _{flax/MAPP})=h1+h2 h _{Flax/MAPP} =2.8+3.6	6.4mm	//	New thickness needed to produce equivalent flexural modulus.
Assuming maximum Power(KW) is 8KW equivalent to 28.8 MJ	Assuming power is 28.8MJ	Assuming power is 28.8MJ	Power of the compression moulding machine remaining the same throughout the process.
Energy is the time(s) multiplied by the power of the moulding machine. Assuming for 1 hour. $\text{Energy}_{\frac{flax}{PLA}} = \frac{(h_{flax/PLA} + h_{newflax/PLA})^2 t}{l^2} \times P$	$\frac{(6.4)^2 \times 3600}{(250)^2} \times 28.8$ =67.95 MJ/h		Energy required to produce the total thickness of the composite flax/MAPP tape.

The thickness required to produce the same flexural modulus like glass UD fibre is 6.4 mm and the energy consumption for moulding is approximately 67.95 MJ/h to produce glass/PP fabrics. The assumptions enables us to estimate the thickness and energy require to produce or improve the mechanical properties during the manufacturing of composite material. Therefore, this theoretical method can be similar to practical, but we can adjust it during the process.

5.10. New energy consumption to increase the flexural modulus of composite material

Table 29 provides the prediction of the energy consumption needed to produce the same flexural modulus base as case 1 to 5. The data was extracted on the case above after the calculations and formula were produced. The new energy consumption varies depending on the thickness and composite materials manufactured. The mechanical properties expected to be achieved can be reached depending on the position of the layers and the process of producing composite material.

Table 29: Natural fibre to reach similar flexural modulus like synthetic material through compression moulding process. The new thickness was produced and the energy consumption required for compression moulding was estimated.

Materials (Cases 1 to 5)	New Thickness to produce	New energy consumption required	Old energy consumption	Flexural modulus to increase
Case1: Flax/PLA to reach Glass UD fabric	5 mm	42MJ/h	18.7MJ/h	20 GPa
Case 2: Flax/PLA to reach Glass UD fabrics	6.4mm	67.95MJ/h	18.7MJ/h	20GPa
Case 3: Flax/MAPP to reach Glass UD fabrics	7.4mm	90.84MJ/h	18.7MJ/h	20GPa
Case 4: Flax/MAPP to reach Glass UD fabrics	8.1mm	108.8MJ/h	18.7MJ/h	7.8GPa
Case 5: Glass/PP fibre to reach Glass UD fabrics	6.4mm	67.95MJ/h	19.1MJ/h	24GPa

Composites natural fibre can have their thickness increased to reach the same flexural modulus like synthetic fibre through compression moulding. The material has different modulus to reach the same flexural modulus. Therefore, Energy consumption to reach the same modulus are different. By increasing the thickness while other dimensions stay the same, the mechanical properties will be improved. The relationship between the five cases are based on the energy consumption and thickness presented in Figure 52.

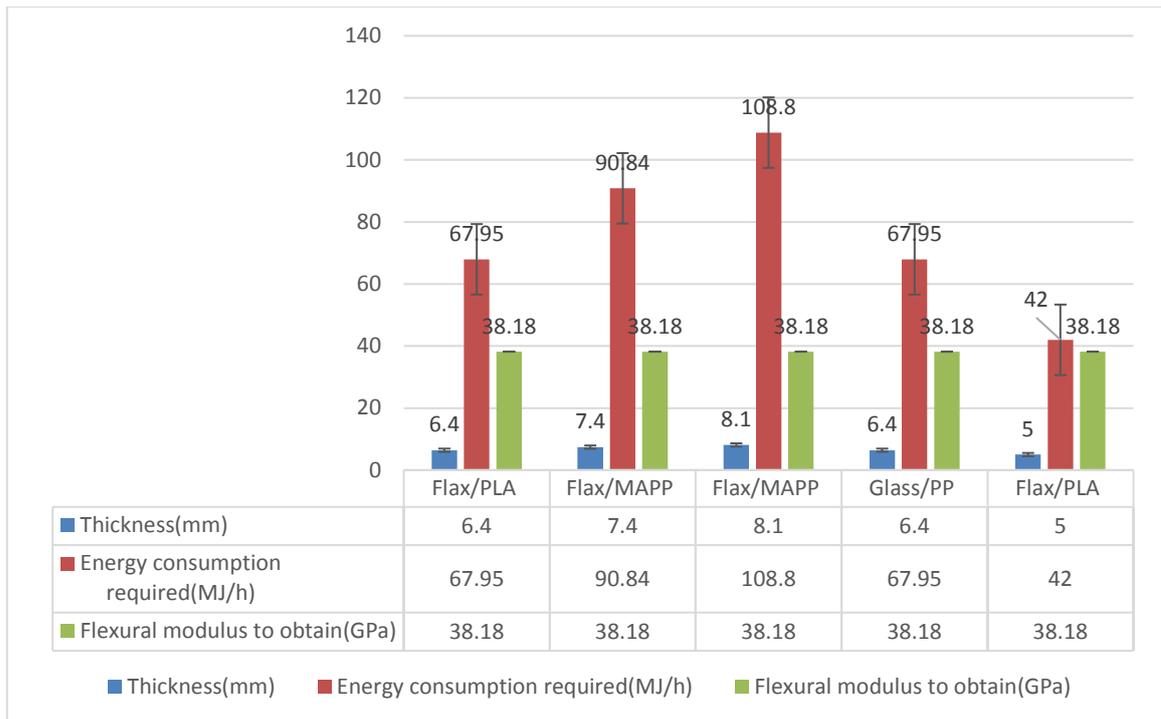


Figure 52: Prediction of the energy consumption using compression moulding and thickness required to produce the same flexural modulus in Table 29 (cases 1 to 5). We can see that flax/MAPP needs more energy consumption and thickness to produce a similar flexural modulus like glass UD fabrics.

The five cases (1 to 5) present different materials and thickness used to produce some amount of energy during production to reach the same flexural modulus indicated at 38.8 GPa. Each material varies depending on the thickness required and energy use but composite glass/PP and flax/PLA have similar thickness of 6.4 mm and same energy consumption mean that thickness have impact on the production process and mechanical properties Composites flax/PLA tape have a lower thickness of 5 mm and lower energy consumption of 42MJ/h. The composite material with high energy consumption shows a lower mechanical property to improve. To reach this modulus, each material requires a different thickness. Therefore, thickness plays an important role in the improvement of mechanical properties. This method can be used for other materials to improve their mechanical propriety. Most materials produce different energy consumption to reach approximately the same modulus, this is due to the thermal properties of each material and the process of manufacturing those materials into the fabric. Moreover, different thickness will produce the same flexural modulus and different carbon dioxide emissions base on energy consumption.

5.11 Simulation on the new energy consumption

The Simapro 8 simulation of the new energy consumption and carbon dioxide emissions produced in Table 29 required to obtain the same flexural modulus. The input of the energy consumption on Simapro 8 gives us the method and carbon dioxide used for this process and environment impact presented in Figure 53. The emissions caused by electricity generation varies across the country due to many factors. Therefore, the simulation is a guideline to manage and inform us about the ecological impact for future generations.

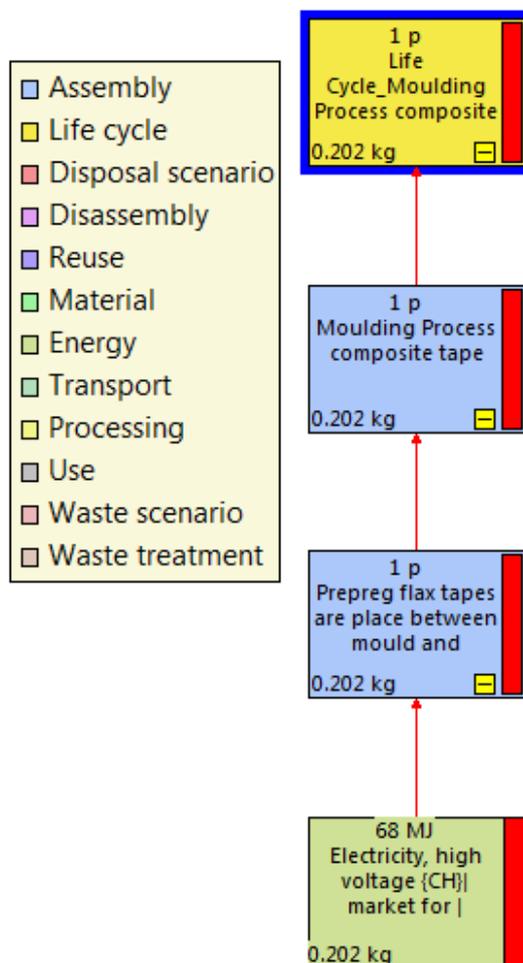


Figure 53: SimaPro 8 simulation of the compression moulding process of the composite flax/PLA tape with the energy consumption at 68 MJ and the carbon dioxide emissions are estimated at 0.202 kg CO₂, therefore, less that one.

The simulation process using Simapro 8 shows the composite flax/PLA tape materials with predictable 6.4 mm thickness and energy consumption at 68 MJ. The red column represented the carbon dioxide at 0.202 kg. The impact on the environment is shown in Figure 54 with three factors (Human health, Ecosystem quality and Resources).

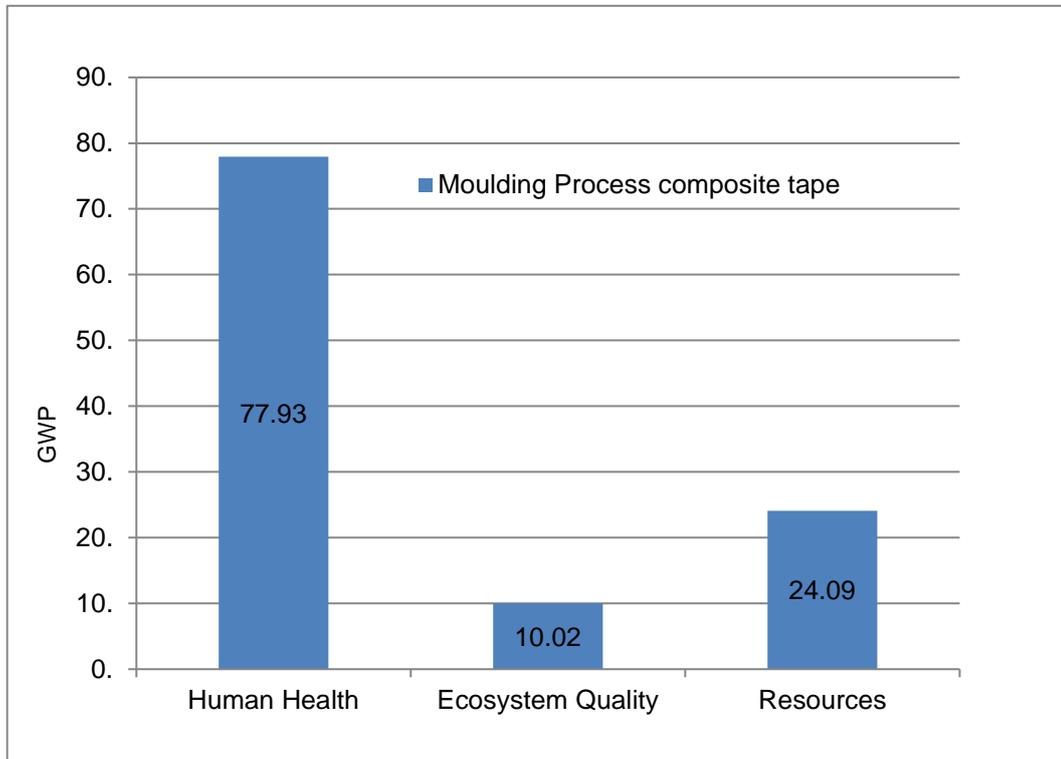


Figure 54: Analyzing 1p (process) `Life Cycle_ Moulding Process composite flax/PLA tape`, Method: Eco-indicator 99 (H) V2.10 / Europe EI 99H/A/ weighting /excluding long-term emissions.

Human health has a higher percentage than resources and ecosystem quality during the moulding process. This is due to the heat released during the heating and cooling time. The information is used to develop a site-specific conceptual model and risk assessment. This involves looking at any potential sources of pollution and assessing the possibility of this reaching the wider environment. The next simulation is presented in Figure 55 process tree.

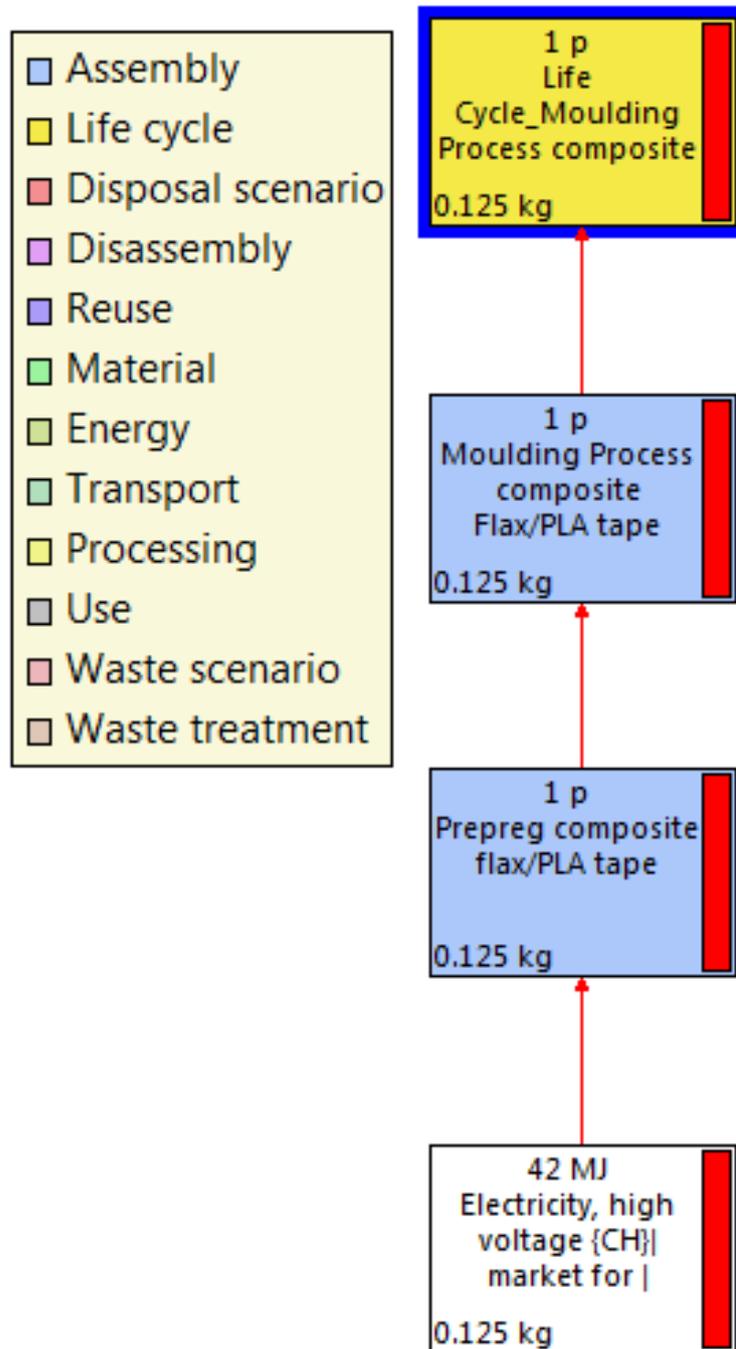


Figure 55: simulation of the compression moulding process of the composite flax/PLA tape with the energy consumption at 42 MJ and the carbon dioxide emissions are estimated at 0.125 kg CO₂, therefore, less than one.

The simulation process using Simapro 8 shows the composite flax/PLA tape with predictable 5 mm thickness and energy consumption at 42 MJ. The red vertical Column represents the carbon dioxide of 0.125 kg. The impact on the environment is shown in Figure 56.

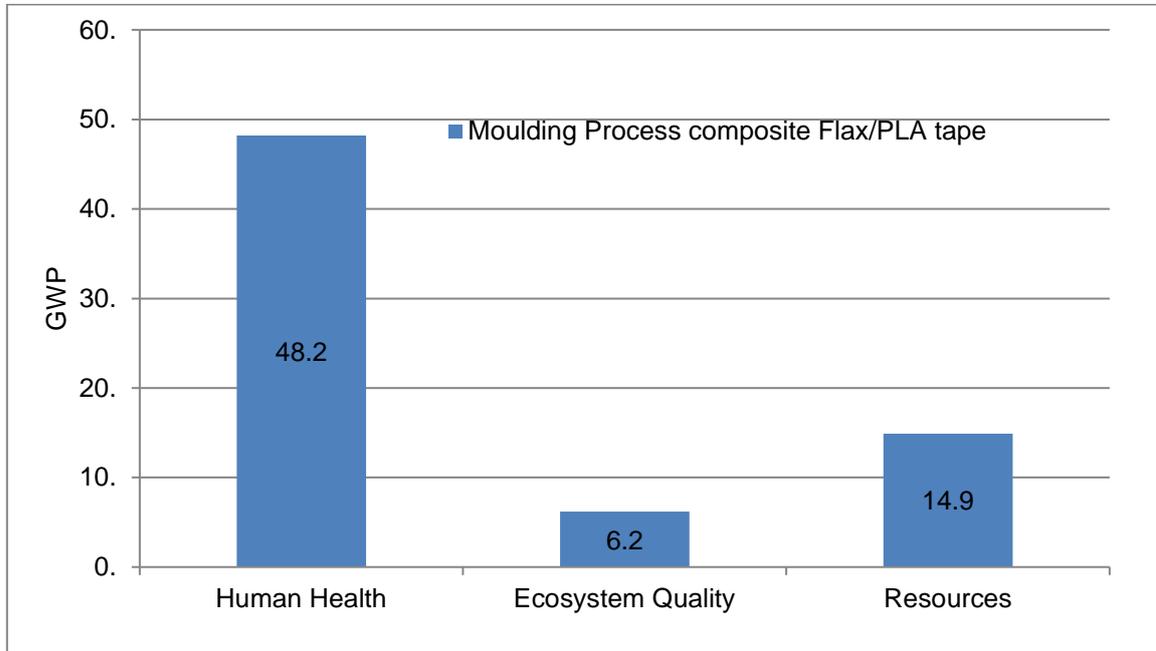


Figure 56: Analyzing 1p (process) `Life Cycle_ Moulding Process composite flax/PLA tape`, Method: Eco-indicator 99 (H) V2.10 / Europe EI 99H/A/ weighting /excluding long-term emissions.

Human health has a higher percentage than resources and ecosystem quality during the moulding process. This is due to the heat released during the heating and cooling time. Figure 57 presents the simulation of the energy consumption at 90.8 MJ/h to produce the process tree.

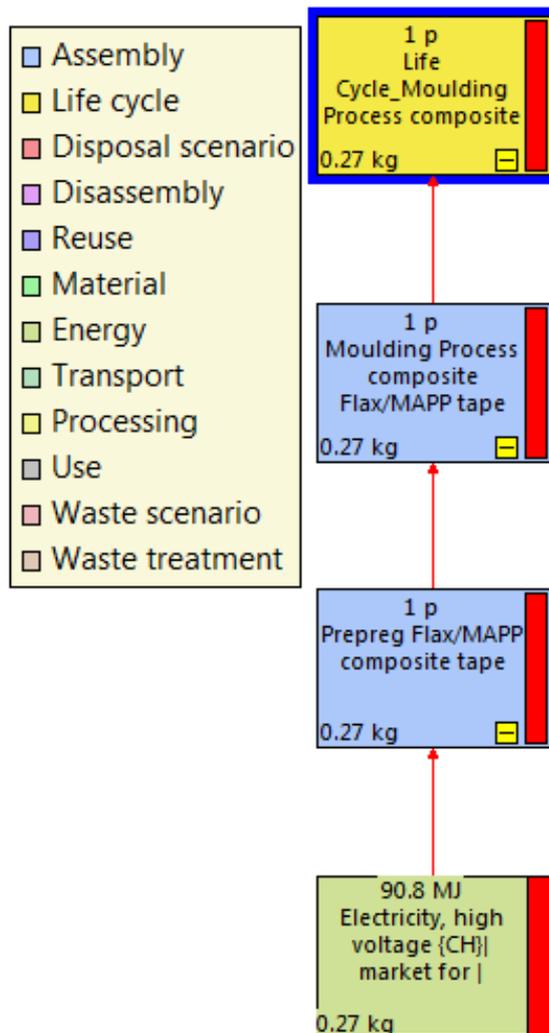


Figure 57: simulation of the compression moulding process of the composite Flax/PLA tape with the energy consumption at 90.8 MJ and the carbon dioxide emissions are estimated at 0.27 kg CO₂, therefore, less than one.

The simulation process using Simapro 8 shows the composite flax/MAPP tape with predictable 7.4 mm thickness and energy consumption at 90.8 MJ. The red vertical Column represents the carbon dioxide of 0.27 kg. The impact on the environment is shown in Figure 58.

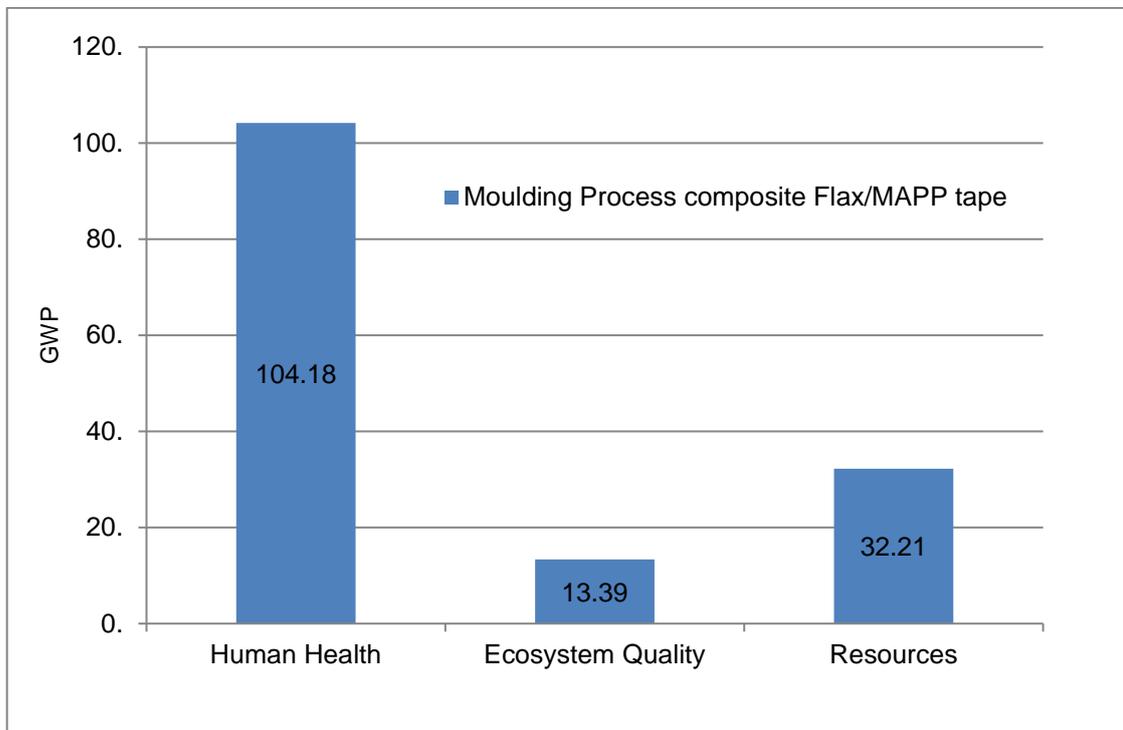


Figure 58: Analyzing 1p (process) `Life Cycle_ Moulding Process composite flax/MAPP tape`, Method: Eco-indicator 99 (H) V2.10 / Europe EI 99H/A/ weighting /excluding long-term emissions.

Human health has a higher percentage of resources and ecosystem quality during the moulding process. This is due to the heat released during the heating and cooling time. Figure 59 presents the simulation of the energy consumption at 109 MJ to produce the process tree.

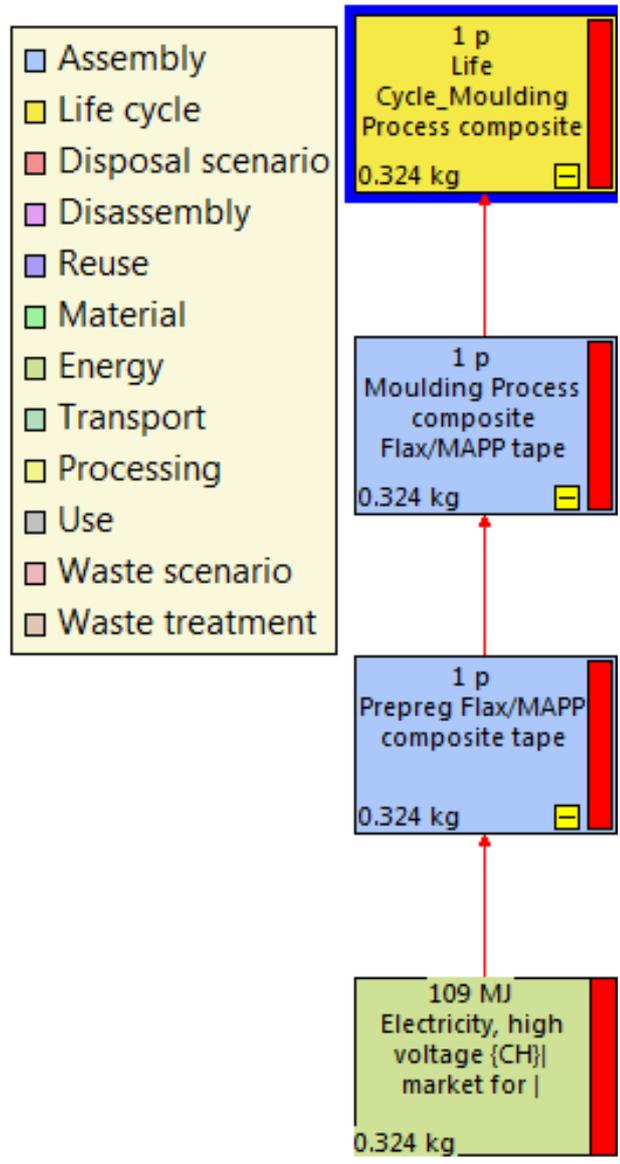


Figure 59: simulation of the compression moulding process of the composite flax/PLA tape with the energy consumption at 109 MJ. The red column show the carbon dioxide emissions are estimated at 0.324 kg CO₂, therefore, less that one.

The simulation process using Simapro 8 shows the composite flax/MAPP tape with predictable 8.1 mm thickness and energy consumption at 109 MJ. The red vertical Column represent the carbon dioxide of 0.324 kg. The environmental impact (Figure 60) are deducted on the process tree.

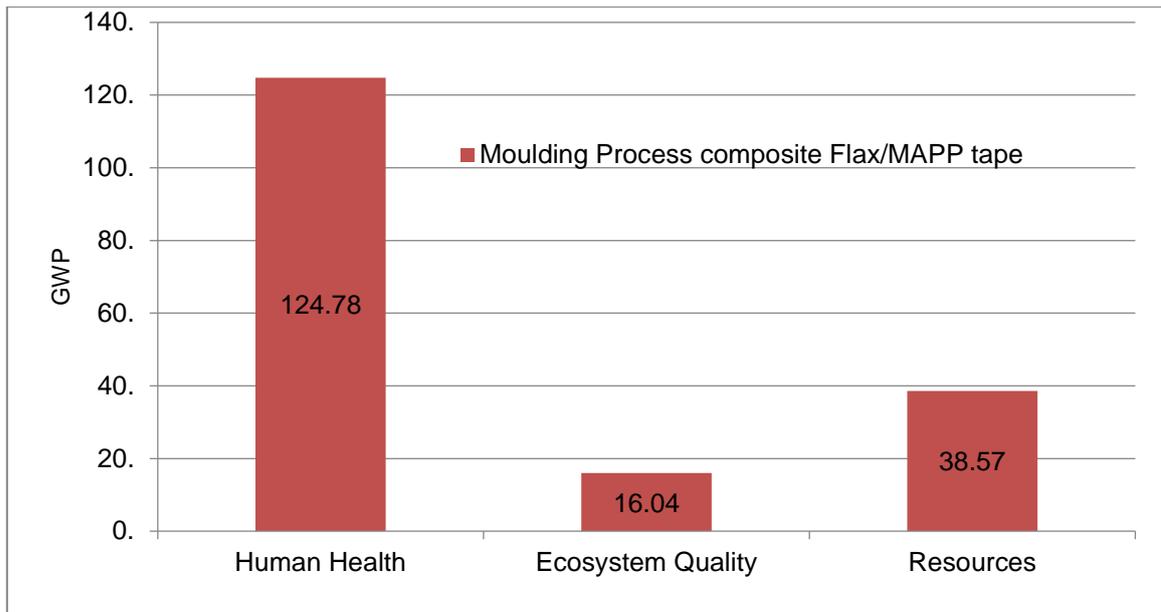


Figure 60: Analyzing 1p `Life Cycle_ Moulding Process composite flax/MAPP tape `, Method: Eco-indicator 99 (H) V2.10 / Europe EI 99H/A/ weighting /excluding long-term emissions.

Human health has a high percentage than resources and ecosystem quality during the moulding process. This is due to the heat released during the heating and cooling time. Figure 61 presents the simulation of the energy consumption at 67.9 MJ to produce the process tree.

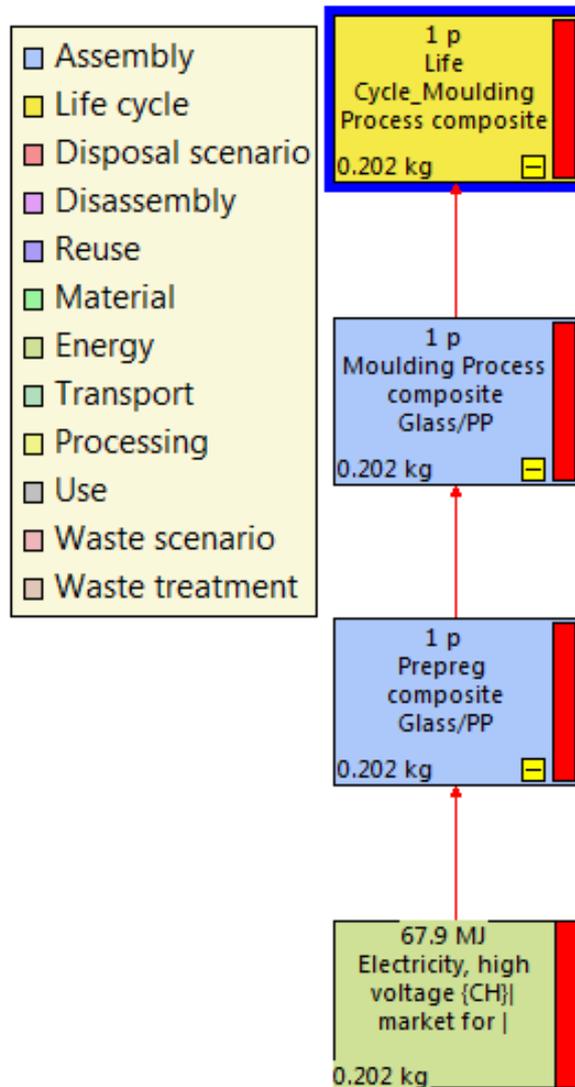


Figure 61: simulation of the compression moulding process of the composite glass/PP with the energy consumption at 67.9 MJ. The red column show the carbon dioxide emissions are estimated at 0.202 kg CO₂, therefore, less that one.

The simulation process using Simapro 8 shows the composite glass/PP materials with predictable 6.4mm thickness and energy consumption at 67.9 MJ .The red vertical Column represent the carbon dioxide of 0.202kg.The impact in the environment is shown on the Figure 62.

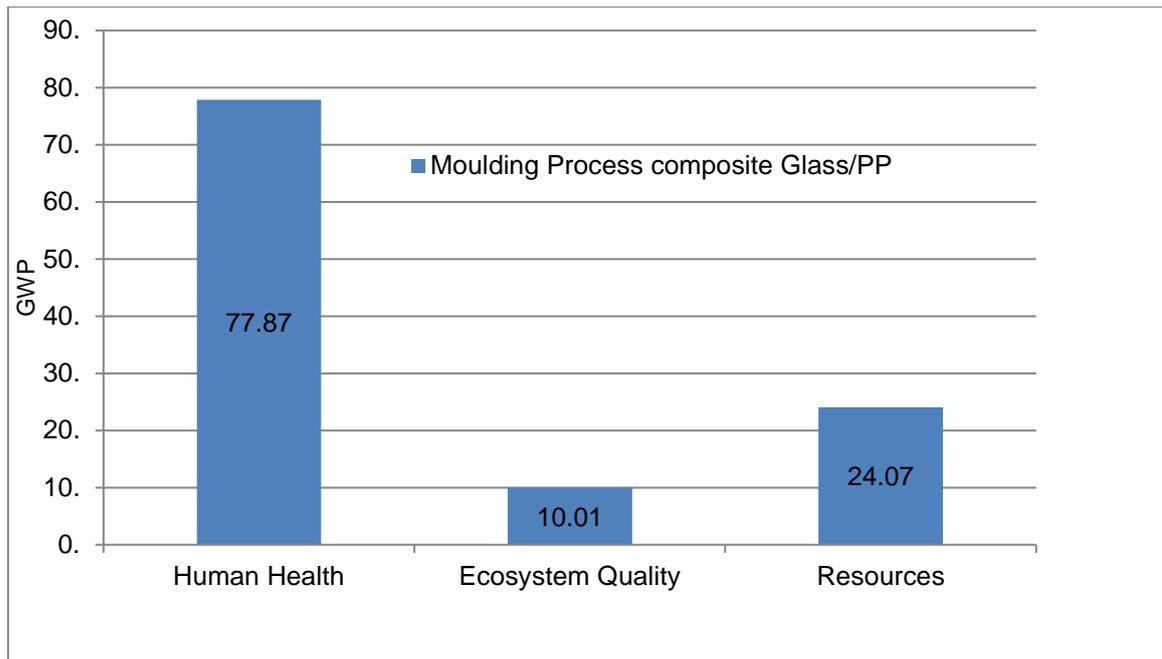


Figure 62: Analyzing 1process `Life Cycle_ Moulding Process composite glass/PP`, Method: Eco-indicator 99 (H) V2.10 / Europe EI 99H/A/ weighting /excluding long-term emissions.

The Human health has a higher percentage than resources and ecosystem quality during moulding process. This is due to the heat released during the heating and cooling time.

5.11.1 Influences on the thickness on the energy consumption and environmental impact cases 1 to 5

The energy consumption and carbon dioxide are represented on the table below based on the SimaPro 8 simulation. The environment impact data was also added on the table to compare a different aspect of the simulation. It will help us to develop a better approach to the choice of composite material and manufacturing. The prediction of the energy consumption shows us approximately how the carbon dioxide gets impacted by the environment. It can be seen that more energy to produce a material may produce more carbon dioxide emissions.

Table 30: Energy consumption and environmental impact of various composite materials case 1 to 5. The environmental impacts, such as human health, ecosystem quality and resources were estimated through simulation for the production of composite materials.

Materials	New energy consumption(MJ)	New carbon dioxide emissions(kgCO ₂)	Human health (%)	Ecosystem Quality (%)	Resources (%)
Case1: Flax/PLA	68	0.202	77.93	10.01	24.09
Case2: Flax/PLA	42.6	0.127	48.9	6.28	15.11
Case3: Flax/MAPP	90.8	0.27	104.18	13.39	32.2
Case4: Flax/MAPP	109	0.324	124.78	16.04	38.57
Case5: Glass/PP	67.9	0.202	77.87	10.01	24.02

Table 30 shows the various composite materials and energy consumption predicted to produce those materials. The simulation using SimaPro 8 shows the carbon dioxide and the environmental impact such as Human health, Ecosystem quality and Resources. This simulation is to influence the same flexural modulus at 38.8 GPa using the compression moulding process. Figure 63 shows the energy consumption and environmental impact based on the production of the new thickness of the composite material.

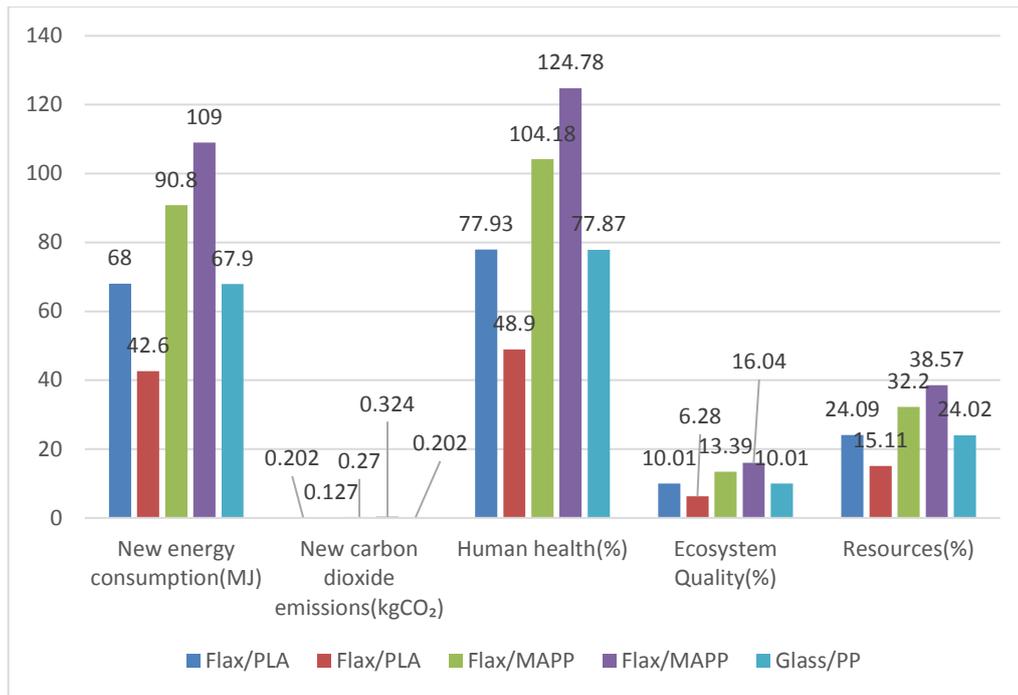


Figure 63: Environmental impact and energy consumption required to produce a similar flexural modulus base on cases 1 to 5. The human health, energy consumption, ecosystem quality and resources for the composite flax/MAPP is higher than other composite materials. The overall carbon dioxide emissions for the production of each composite material is less than one.

This bar chart illustrates the energy consumptions and environmental impact of the case 1 to 5 of the composite material that was used for compression moulding. It also indicates future projections of the energy consumption and environmental impact for the production of composite materials to reach the level of flexural modulus approximately at 38.8GPa. It shows that the energy consumption of all five (cases 1 to 5) materials varies from 42 MJ to 109 MJ. The human health for the production, using composite moulding processing, shows the lower reading at 42.9 % and the higher at 124.78%. The ecosystem quality and resources vary between 6.28 and 38.57%. We can see that energy consumption shows no impact on the environment, with less than 1% of carbon dioxide produced for each composite moulding process. Altogether, the present simulations provides novel observations, measurements and interpretations to be used in the further development and understanding of the natural fibre composites.

5.12. Overview of the new composite material for the automotive industry

We used a steady-state model to evaluate potential manufacturing of natural fibre composite and environmental implications of composites flax/PLA tape and flax/MAPP tapes for automotive body panels on a part-by-part basis. A major materials substitution in the automotive industry would have to occur incrementally rather than in a radical and disruptive complete material substitution.

Realistically, the results presented here would take a long time to be realized. A more robust model, such as Eco-indicator based life cycle assessment shown in Chapter 2 Section 2.3., can be used to evaluate ecological implications over time. Consideration of complete material specification for some car body design changes for the automotive industry, the optimum performance is based on the specific properties of hybrid natural composites material fabric which may lead to considerably different composite material grades.

Current levels of uncertainty concerning the performance of the natural composite lead to constructing lower and upper bounds which can be improved through mechanical properties. The test results in Chapter 4, Section 4.6.6, Figure 37 show that glass UD fabrics have high flexural modulus that flax/PLA and other materials based on the thickness. Therefore, Case 1 to 5 in Chapter 5, Section 5.10 Table 29 predicted a method to improve mechanical properties by an increasing thickness which may lead to high energy consumption. Uncertainty about the costs of using this material in the body fabrication leads to estimating the value of the natural composite fabric as a function of its efficiency that can be used to replace other non-composite material.

The production of natural composite flax/PLA tape is approximately 338.4 kg and the energy consumption is 32.54 MJ per day based in Tilsatec Chapter 4 Section 4.1.4. , Table 15 page 82, compared to aluminum with 196-257 MJ/kg based in Chapter 2, Section 2.3.3 Table 6 page 37. More energy consumption leads to high carbon dioxide emission during production and the composite material could be a competitive material that would increase fuel economy at low cost. Greater fuel economy leads to potentially large economic and environmental benefits.

The carbon dioxide reduction during the lifetime use of motor vehicles is a large potential benefit. However, more developing country consumers have little interest in greater fuel economy, and so this technology is unlikely to be developed and employed in this application without government intervention. Composite material costs less than other conventional materials like aluminum and offer better mechanical properties.

We did not consider other materials that already demonstrated significant weight savings potential in automotive applications. Examples include advance high strength steel, magnesium, glass fibre reinforced polymers, carbon-reinforced polymers and metal matrix composites. We did consider other environmentally friendly composite material such as composite flax/PLA, and flax/MAPP tape that can be combined with other materials part such as parcel shelf, door insert and instrument panel.

The future composition of the vehicle will be determined by intensive competition among the future cost/performance ratios of candidate materials demonstrated in Chapter 4, Section 4.3.5 Figure 29. The production cost for natural and synthetic materials are much lower than for steel, but steel is ideal for mass production of vehicles. Our analysis shows that natural composite materials flax/PLA tape and glass fibre fabric offer considerable weight reduction and environmental saving as compared to steel, but vehicle manufacturers have not made the substitution.

Composite flax/PLA and flax/MAPP tape have been identified as having several potential advantages over those traditionally made plastic materials. However the complex behaviour of natural composite materials makes it difficult and complex to perform a valid structure analysis. Modelling outputs of composite flax/PLA and MAPP tape materials samples can be compared with compression test data for validation after repeating some test data with accurate results.

To displace natural composite, a lightweight material must offer much larger savings or other advantages (such as hybrid composite flax/PLA materials with high mechanical properties standard). The composite materials are required to pay for its additional cost and satisfy the suppliers with any other structural and functional requirements in order to induce manufacturers to re-engineer their vehicles for the new material. One major advantage of composite materials over metals is the ability to fabricate aesthetically pleasing complex shapes. While this is not an environmental saving, this benefit coupled with higher fuel economy could entice consumers to purchase the lower weight vehicles, thus reducing environmental impact.

Chapter 6: Conclusion and Future work

6.1 Conclusion

Natural fibres are a renewable resource with production requiring little energy. They are carbon neutral, i.e. they do not return excess carbon dioxide into the atmosphere when they are composted or combusted. The processing atmosphere is friendly with better working conditions and therefore there will be reduced dermal and respiratory irritations. At the end of their life, they can be easily disposed of or composted without harming the environment.

In this work, a new system for producing natural composite flax/PLA tape was developed. Flax/PLA tape was chosen to be the fibre for this research, because of its' tensile properties, thermal properties, price and availability. Natural fibres behave differently in different atmospheric conditions, but even under extreme conditions, the fibres show excellent properties. Development of a flax/PLA distributor, good impregnation of the prepreg between compaction rolls, drying the flax/PLA. Before impregnation and monitoring the maturation, we observed the flow of the flax/PLA tape, to extremities of the mould during compression moulding, which resulted in a homogenous flax/PLA tape product. From the mechanical properties data, we can see that varying the flax/PLA tape percentages, and fibre layer direction led to the result that the stiffness of the composite flax/PLA tape moulding is equal to or even slightly better than the rigidity of the glass fibre or polypropylene (PP) . Increasing the fibre thickness led to an enormous improvement of the tensile and flexural modulus, which resulted in exceptional results to that of glass fibre moulding component. From this work, it concluded that for products designed concerning stiffness and to a lesser extent, strength flax/PLA composite materials could compete with glass fibre moulding composite material.

The selection of natural fibre and matrix systems is the key to assessing a lower embodied energy with some of the most significant advantages. All-natural fibre composites can provide a lower density compared to synthetic materials like glass fibre, PP materials. The natural fibre composites can provide higher specific rigidity under the same weight, which is an excellent selling point or in competing with overall composite glass fibre or E-glass. Meanwhile, the embodied energy of most of the natural fibre composites is less or similar to the glass fibre composites under the same weight while providing higher or equivalent stiffness. Therefore, under the same weight scale, natural fibre composites can provide a higher rigidity.

The graph shows the environmental impact of the composite materials studies above and we see that some material like PLA and flax can be recycled with less energy used and are naturally biodegradable. Polypropylene (PP) and glass roving are not biodegradable and the percentage that is able to be recycled is lower than other composite materials. If global warming potential is less than one, the production of material does not have any impact on the environment. The findings suggest that the energy consumption of glass and PP are reduced in different ways. The first method is to reduce the high energy consumption of raw material extraction using alternative raw materials with low energy consumption. The second method is to implement the process to commingle different natural composite materials in to fabrics to improve compatibility and reduce energy consumption.

6.2 Future work

In the first results obtained from the current study, several directions are available drawing attention for further research.

The expected service life based on the reliability of flax, combined with PLA or MAPP fibre and other natural materials, compared to some synthetic materials like Glass fibre reinforced plastic, or other synthetic materials production, needs additional investigation. The natural fibres have some environmental advantages over glass fibres they also possess some disadvantages. Natural bio-composites fibres can easily compete with glass fibres in terms of stiffness as predicted in Chapter 5. However, the tensile strength and flexural modulus of natural composites fibre are relatively low compared to composites glass fibre or poly-propylene. Natural fibre materials particularly suffer from this because the materials, which they have to replace, glass unit directional fibre, is often selected over, for example sheet moulding compounds, because of their superior flexural modulus performance and other characteristics.

The study of interfacial adhesion, which is a well-known problem for natural fibres and synthetic polymers, also shows that adhesion needs to be improved to optimise the mechanical properties of some natural fibre composites. This work can be investigated by scanning the cross-section area of the composite flax/PLA or flax/MAPP tape and Glass/PP using a Scanning Electron Microscope (SEM) to analyse the connection between the fibre and the resin matrix. The geometry of the fibre composite flax/PLA or MAPP tape and Glass/PP or triaxial glass fibre fabric will be scanned and imported into a finite element analysis software package to create a workable testing simulation model. The method can be then validated by comparing the finite element analysis (FEA) model with experimental results of triaxial glass fibre or glass/PP. This will result in a better selection of the manufacturing of composite materials. With further investigation, this will improve the mechanical properties and thermal properties of the natural fibre compare to synthetic fibre. Due to a highly integrated product with lower energy consumption and environmental impact, the ability to be biodegradable after the end of its life, can be selected rather than synthetic material that has more or less the same characteristics.

The first aspect is associated with a life assessment for the composite material process. This study uses LCA Simapro 8 and Ecoinvent, to establish the process tree and environmental impact, to produce the results of the manufacturing of the composite materials. Future work could try other available packages of LCA such as GABI education, Eco-point and Eco indicator 95 software to evaluate the outcome of the material transformation and other manufacturing processes. The current method

evaluates the system boundary for the input and output of the processed materials. It would be beneficial to have a standard approach to work out for the evaluation of energy consumption and carbon dioxide emissions.

The outcomes of the LCA gate to gate studies could be highly sensitive to the applied allocation methods. This methodology issue is very challenging and essential because environmental concerns are the main driver for the development and introduction of composite flax/PLA tape and bio-based materials. The current study evaluated the process tree and the environmental impact of each manufacturing process. Another complicated aspect in this domain is the combination allocation to compare the environmental impact through the same allocation method because the final results are then inconsistent and are hard to interpret. As the number of LCA gate-to-gate is minimal and probably the greatest difficulty to record, with a data gap involved in assessing the production processes. Principally there are some newly developed methods and composite materials.

Final element analysis to simulate the increased thickness of the composite flax/PLA tape and glass/PP materials, will improve the overall mechanical properties such as deformation, torsion for a non-destructive test method. They will lead to a better improvement and number of layers to use and overcome the mechanical properties. More evaluation such as sound insulation test using an incubator tube to measure and compare the decibel (dB) of the new composite flax/PLA tape. The plasma infusion of the treatment of the surface of the natural composite material to reduce the absorptivity of water. It's essential to support the use of LCA tool in the early planning stage and other test methods that can be useful for the advance and progress of new natural composite materials.

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APPENDIX

Appendix A:

1.A-Properties of bast fibre [239].

Fibers	Modulus (GPa)	Strength (MPa)	Density (g/cm ³)	Specific Modulus	Specific Strength
E-glass	72	3530	2.54	28.2	1390
Flax	50-70	500-900	1.4-1.5	~ 41	~ 480
Hemp	30-60	300-800	1.48	~ 30	~ 370
Jute	20-55	200-500	1.3-1.5	~ 27	~ 250

2.A-Mechanical Properties of natural fibre and cost [239].

Material	Density (g/cc)	Tensile strength (MPa)	Elastic modulus (GPa)	Specific strength (σ/γ)	Specific modulus (E/γ)	Elongation at failure (%)	Moisture absorption (%)	Cost (\$/lb)
E-glass ¹¹	2.62	3400	73	1297	28	4.8	N/A	1.10
Hemp ¹²	1.4	550-900	70	393-643	50	1.6	6-12	0.30
Flax ¹³	1.4	800-1500	60-80	571-1071	43-57	2.7-3.2	8-12	0.33
Ramie ¹⁴	1.5	500	44	333	29	3.6-3.8	8-17	0.34
Kenaf ¹⁴	1.45	930	53	641	36	1.6	10-12	0.24
Coir ¹³	1.25	220	6	176	5	1.5-4	8	0.20
Sisal ¹³	1.33	600-700	38	451-526	29	3-7	10-22	0.36
Jute ¹³	1.46	400-800	10-30	281-548	7-21	1.5	12-14	0.20

3.A -Supplier and prices of fibre.

Fibre type	Semi-product type	Specification	Supplier	Price (€/kg)
Hemp	Raw fibres		Hemcore Ltd (UK)	0.6
Flax	Raw fibres		Bio-7-Fibers (DK)	0.6
Glass	Chopped strands		Owens Corning (CA)	1.5
Hemp	Non-woven mat	1500 g/m ²	Bio-7-Fibers (DK)	1.8
Flax	Non-woven mat	1500 g/m ²	Bio-7-Fibers (DK)	1.8
Glass	Strand mat	150 g/m ²	Owens Corning (CA)	2.6
Hemp	Yarn	50 tex	Linificio e Canapificio (I)	16.3
Flax	Yarn	60 tex	Linificio e Canapificio (I)	11.6
Jute	Yarn	140 tex	Himanshu Jute Fab (IN)	1.6
Cotton	Yarn	50 tex	Textil Manual Goncalves (PT)	3.4
Glass	Roving	100 tex	Owens Corning (CA)	2.5
Carbon	Roving	800 tex	Toray (JP)	18.9

4. A. Natural fibre selection for composite lamination, cost and mechanical properties. The data has been selected in appendices one and two on the materials selection [223-225].

Materials	Density(g/cm ³)	Tensile strength(MPa)	Flexural modulus(GPa)	Cost(£/kg)
Polypropylene sliver(PP)	0.94	29	1.94	0.88
Maleinised Polypropylene sliver(MAPP)	0.99	20.18	1.94	0.88
Poly lactide acid(PLA)	1.25	50	4	3.91
Flax fibre	1.45	800-1500	43-57	9.83£/kg
Glass fibre	2.6	3400	72	2.27£/kg

5.A Natural fibre production [240]

Inputs					
Materials ^a	Units	Value	Energy	Units	Value
Seeds	kg	50.00	Electricity for scutching	kWh	336
Fertilizers			Transportation		
Ammonium nitrate	kg N	85.00	Fertilizers	t km	90.48
Triple superphosphate	kg P ₂ O ₅	65.00	Fibre bales	t km	180.00
Potassium chloride	kg K ₂ O	125.00			
Diesel	kg	74.85			
Agricultural machinery	kg	23.05			
Outputs					
Products and co-products			Units	Value	
Straw (11–14% moisture)			t		3.00
Fibre			t		1.00
Woody core			t		1.50
Hemp dust			t		0.50

6.A Energy intensity of steel and carbon fibre [241]

	Steel (MJ/kg)	CF (MJ/kg)	
		In 1999	In 2004
Raw material production	-	42	39
Processing and assembly	-	436	247
Total	33	478	286

7.A Energy intensity of matrix resins [241]

	Energy intensity (MJ/kg)
Epoxy	76.0
Unsaturated polyester	62.8
Phenol	32.9
Flexible polyurethane	67.3
High-density polyethylene	20.3
Polypropylene	24.4

8.A Energy intensity of prepreg production [241]

Production process	Energy intensity (MJ/kg)
Resin blending	0.1
Resin coating	1.4
Resin impregnation	2.1
Prepreg winding	0.2
Atmosphere control	20.8
Raw material storage	11.5
Prepreg storage	3.4
Release coated paper production	0.5
Total	40.0

9.A Energy intensity of moulding [241]

Molding method	Energy intensity (MJ/kg)
Hand lay up	19.2
Spray up	14.9
RTM	12.8
VARI	10.2
Cold press	11.8
Preform matched die	10.1
SMC	3.5
Filament winding	2.7
Pultrusion	3.1

10.A Energy consumption in glass fibre production [10]

Producer	natural gas MJ	electricity kWh
Sisecam ¹¹ (Turkey)	17,173	1.13
Vetrotex Germany (finer filaments)	23,040	2.5
Vetrotex Germany EC14-300 P185	28,080	1.2
Vetrotex International	19,180	1.68
PPG ¹²	17,250	1.6
OwensCorning (USA)	10,500	0.58
OwensCorning ac. to Chalmers (GB)	23,159	0.55

11.A Inputs for the production of glass fibre tissue [10]

inputs	glass fiber	unit
electricity	0.1093	kWh/m ²
steam	0.8	kg/m ²
gas	0.0188	m ³ /m ³
electricity(furnishing)	0.09	kWh/m ²

12.A Typical electricity consumption for UD-production [10]

fiber	electricity consumption	unit
carbon fibers	0,052	kWh/m ²
aramid fibers	0,029	kWh/m ²
glass fibers	0,038	kWh/m ²

13. A Material properties of PLA [240]

Material properties of PLA.

	Nature works PLA	Biomer L9000
<i>Physical properties</i>		
Melt flow rate (g/10 min)	4.3–2.4	3–6
Density (g/cm ³)	1.25	1.25
Haze	2.2	
Yellowness index	20–60	
<i>Mechanical properties</i>		
Tensile strength at yield (Mpa)	53	70
Elongation at yield (%)	10–100	2.4
Flexular modulus (Mpa)	350–450	3600
<i>Thermal properties</i>		
HDT (°C)	40–45, 135	
VICAT Softening point (°C)		56
GTT (°C)	55–56	
Melting point	120–170 ⁴	

Appendix B:

1. B Mechanical properties of pure PP matrices and PP/SGF composites treated with various amounts of coupling agents.

Composite	σ_T (MPa)	E_T (GPa)	σ_F (MPa)	E_F (GPa)	IS (J/m)
PP	21.0 ± 0.8	0.8 ± 0.032	47.9 ± 1.3	1.3 ± 0.051	44.8 ± 0.0
PP/SGF25	67.6 ± 0.9	1.9 ± 0.026	99.3 ± 2.7	3.5 ± 0.045	73.7 ± 3.3
PP-g-MA (2 wt %)	76.8 ± 0.2	1.9 ± 0.008	120.0 ± 4.2	3.2 ± 0.268	101.9 ± 7.5
PP-g-MA (4 wt %)	77.7 ± 0.4	1.9 ± 0.013	123.3 ± 1.0	3.4 ± 0.031	103.5 ± 10.1
PP-g-MA (6 wt %)	80.0 ± 0.6	2.0 ± 0.022	127.2 ± 0.9	3.5 ± 0.032	103.5 ± 3.6
PP-g-MA (8 wt %)	79.0 ± 0.5	2.0 ± 0.016	123.4 ± 2.8	3.6 ± 0.035	97.5 ± 5.6
SEBS-g-MA (2 wt %)	61.3 ± 1.5	1.8 ± 0.035	97.8 ± 2.9	3.2 ± 0.320	77.7 ± 0.0
SEBS-g-MA (4 wt %)	57.8 ± 0.9	1.8 ± 0.014	90.6 ± 1.0	3.2 ± 0.031	82.0 ± 3.5
SEBS-g-MA (6 wt %)	53.4 ± 0.8	1.7 ± 0.016	84.8 ± 1.0	3.0 ± 0.052	86.2 ± 2.7
SEBS-g-MA (8 wt %)	50.6 ± 0.9	1.7 ± 0.012	81.4 ± 1.2	2.9 ± 0.076	90.3 ± 2.7

2. B. Materials prices and mechanical properties

MATERIAL	Type	Cost (\$/kg)	Density (ρ , Mg/m ³)	Young's Modulus (E, GPa)	Shear Modulus (G, GPa)	Poisson's Ratio (ν)	Yield Stress (σ_y , MPa)	UTS (σ_t , MPa)	Breaking strain	Fracture Toughness	Thermal Expansion (α)
Alumina (Al ₂ O ₃)	ceramic	1.90	3.9	390	125	0.2	480	35	0.0	4.4	8.1
Aluminum alloy (7075-T6)	metal	1.80	2.7	70	28	0.3	500	570	12	28	33
Beryllium alloy	metal	315.00	2.9	245	110	0.1	360	500	6.0	5.0	14
Bone (compact)	natural	1.90	2.0	14	3.5	0.4	100	100	9.0	5.0	20
Brass (70Cu30Zn, annealed)	metal	2.20	8.4	130	39	0.3	75	325	70	80	20
Cermets (Co/WC)	composite	78.60	11.	470	200	0.3	650	120	2.5	13	5.8
CFRP Laminate (graphite)	composite	110.00	1.5	1.5	53	0.2	200	550	2.0	38	12
Concrete	ceramic	0.05	2.5	48	20	0.2	25	3.0	0.0	0.75	11
Copper alloys	metal	2.25	8.3	135	50	0.3	510	720	0.3	94	18
Cork	natural	9.95	0.1	0.03	0.00	0.2	1.4	1.5	80	0.074	180
Epoxy thermoset	polymer	5.50	1.2	3.5	1.4	0.2	45	45	4.0	0.50	60
GFRP Laminate (glass)	composite	3.90	1.8	26	10	0.2	125	530	2.0	40	19
Glass (soda)	ceramic	1.35	2.5	65	26	0.2	350	35	0.0	0.71	8.8
Granite	ceramic	3.15	2.6	66	26	0.2	250	60	0.1	1.5	6.5
Ice (H ₂ O)	ceramic	0.23	0.9	9.1	3.6	0.2	85	6.5	0.0	0.11	55
Lead alloys	metal	1.20	11.	16	5.5	0.4	33	42	60	40	29
Nickel alloys	metal	6.10	8.5	180	70	0.3	900	120	30	93	13
Polyamide (nylon)	polymer	4.30	1.1	3.0	0.7	0.4	40	55	5.0	3.0	103
Polybutadiene elastomer	polymer	1.20	0.9	0.001	0.000	0.5	2.1	2.1	500	0.087	140
Polycarbonate	polymer	4.90	1.2	2.7	0.9	0.4	70	77	60	2.6	70
Polyester thermoset	polymer	3.00	1.3	3.5	1.4	0.2	50	0.7	2.0	0.70	150
Polyethylene (HDPE)	polymer	1.00	0.9	0.7	0.3	0.4	25	33	90	3.5	225
Polypropylene	polymer	1.10	0.8	0.9	0.4	0.4	35	45	90	3.0	85
Polyurethane elastomer	polymer	4.00	1.2	0.02	0.008	0.5	30	30	500	0.30	125
Polyvinyl chloride (rigid PVC)	polymer	1.50	1.4	1.5	0.6	0.4	53	60	50	0.54	75
Silicon	ceramic	2.35	2.3	110	44	0.2	320	35	0.0	1.5	6
Silicon Carbide (SiC)	ceramic	36.00	2.8	450	190	0.1	980	35	0.0	4.2	4.2
Spruce (parallel to grain)	natural	1.00	0.6	9	0.8	0.3	48	50	10	2.5	4
Steel, high strength 4340	metal	0.25	7.8	210	76	0.2	124	155	2.5	100	14
Steel, mild 1020	metal	0.50	7.8	210	76	0.2	200	380	25	140	14
Steel, stainless austenitic 304	metal	2.70	7.8	210	76	0.2	240	590	60	50	17
Titanium alloy (6Al4V)	metal	16.25	4.5	100	39	0.3	910	950	15	85	9.4
Tungsten Carbide (WC)	ceramic	50.00	15.	550	270	0.2	680	35	0.0	3.7	5.8

3.B. Fibre volume Fraction and weight ratio Relationship [242]

The resin weight is the difference between the composite and fibre weights:

$$W_{\text{resin}} = W_{\text{composite}} - W_{\text{fibre}}$$

Calculate the fibre/resin volume ratio:

$$\frac{V_{\text{fibre}}}{V_{\text{resin}}} = \left(\frac{W_{\text{fibre}}}{W_{\text{resin}}} \right) \left(\frac{\rho_{\text{resin}}}{\rho_{\text{fibre}}} \right) \quad v_f = \frac{\frac{W_f}{\rho_f}}{\frac{W_f}{\rho_f} + \frac{W_m}{\rho_m}} = \frac{\frac{w_f}{\rho_f}}{\frac{w_f}{\rho_f} + \frac{w_m}{\rho_m}}$$

Matrix volume ratio

$$V_m = \frac{1}{1 + \left(\frac{V_{\text{fibre}}}{V_{\text{resin}}} \right)}$$

Appendix C:

1.C Carbon Footprint: Calculating our Carbon Footprint [212]

Base electricity generation emission factors (excluding imported electricity) [217]

Data Year	Emission Factor, kgCO _{2e} / kWh												% Net Electricity Imports
	For electricity GENERATED (supplied to the grid)				Due to grid transmission /distribution LOSSES				For electricity CONSUMED (includes grid losses)				
	CO ₂	CH ₄	N ₂ O	Total	CO ₂	CH ₄	N ₂ O	Total	CO ₂	CH ₄	N ₂ O	Total	
2009	0.45211	0.00027	0.00263	0.45501	0.03783	0.00002	0.00024	0.03809	0.49074	0.0003	0.00285	0.49389	0.80%
2010	0.4598	0.00028	0.00269	0.46277	0.05061	0.00001	0.00042	0.05104	0.49613	0.0003	0.0029	0.49933	0.73%
2011	0.44877	0.00029	0.00285	0.45192	0.04318	0.00001	0.00033	0.04352	0.48715	0.00032	0.0031	0.49056	1.76%
2012	0.5052	0.00034	0.00381	0.50935	0.04418	0.00003	0.00033	0.04454	0.54938	0.00037	0.00414	0.55389	3.40%
2013	0.4753	0.0004	0.0035	0.4791	0.0392	0.0000	0.0003	0.0396	0.5146	0.0004	0.0038	0.5187	4.10%
2014	0.42417	0.00040	0.00217	0.42673	0.03837	0.00004	0.00020	0.03860	0.46254	0.00044	0.00236	0.46534	6.44%
2015	0.35766	0.00064	0.00214	0.36044	0.03343	0.00006	0.00020	0.03369	0.39108	0.00070	0.00234	0.39412	6.59%
2016	0.28266	0.00066	0.00154	0.28486	0.02409	0.00006	0.00013	0.02428	0.30675	0.00072	0.00167	0.30913	5.57%
2017	0.25294	0.00065	0.00137	0.25496	0.02148	0.00005	0.00012	0.02165	0.27442	0.00070	0.00149	0.27660	4.78%

Notes: * From 1990-2013 the emission factor used was for French electricity only, and is as published in previous methodology papers. The methodology was updated from 2014 onwards with new data on the contribution of electricity from the other interconnectors, hence these figures are based on a weighted average emission factor of the emission factors for France, the Netherlands and Ireland, based on the % share supplied.

Time series data in light grey is locked/fixed for the purposes of company reporting and has not been updated in the database in the 2019 GHG Conversion Factors update.

Emission Factor (Electricity CONSUMED) = Emission Factor (Electricity GENERATED) / (1 - %Electricity Total Grid LOSSES)

Emission Factor (Electricity LOSSES) = Emission Factor (Electricity CONSUMED) - Emission Factor (Electricity GENERATED)

⇒ Emission Factor (Electricity CONSUMED) = Emission Factor (Electricity GENERATED) + Emission Factor (Electricity LOSSES),

Time series data in light grey is locked/fixed for the purposes of company reporting and has not been updated in the database in the 2019 GHG Conversion Factors update [217].

Emission Factor (Electricity CONSUMED) = Emission Factor (Electricity GENERATED) / (1 - %Electricity Total Grid LOSSES) [217]

Emission Factor (Electricity LOSSES) = Emission Factor (Electricity CONSUMED) - Emission Factor (Electricity GENERATED)

⇒ Emission Factor (Electricity CONSUMED) = Emission Factor (Electricity GENERATED) + Emission Factor (Electricity LOSSES) [217],

Convert kWh electricity to kg CO₂

In order to convert electricity consumed in kWh to kg of carbon dioxide, the energy use should be multiplied by a conversion factor. This factor changes from year to year, as the fuel mix consumed in UK power stations changes.

2.C.The conversion factors for energy sources are: [212]

Energy Source (kWh)	Conversion factor (kg CO ₂ / kWh)
Electricity	0.523
Natural gas	0.185
Burning oil (for heating)	0.245

How do I calculate my GHG emissions for a particular activity?

GHG emissions = activity data x emission conversion factor

3. C Table 1. Specific heat and thermal diffusivity of HDPE and flax fiber–HDPE(high density polyethylene) bio composites [183].

Materials	Temperature (°C)	Specific heat (kJ/kg°C)		Thermal diffusivity (m ² /s)	
		Mean	Standard deviation	Mean	Standard deviation ^b
10% fiber biocomposite ^a	170	2.44	0.01	1.68 × 10 ⁻⁷	7.45 × 10 ⁻⁹
	180	2.47	0.02	1.66 × 10 ⁻⁷	7.49 × 10 ⁻⁹
	190	2.50	0.04	1.64 × 10 ⁻⁷	7.62 × 10 ⁻⁹
	200	2.52	0.04	1.63 × 10 ⁻⁷	7.69 × 10 ⁻⁹
20% fiber biocomposite ^a	170	2.28	0.02	1.59 × 10 ⁻⁷	1.51 × 10 ⁻⁸
	180	2.29	0.01	1.58 × 10 ⁻⁷	1.50 × 10 ⁻⁸
	190	2.32	0.01	1.56 × 10 ⁻⁷	1.48 × 10 ⁻⁸
	200	2.34	0.01	1.55 × 10 ⁻⁷	1.47 × 10 ⁻⁸
30% fiber biocomposite ^a	170	2.25	0.02	1.40 × 10 ⁻⁷	1.34 × 10 ⁻⁸
	180	2.27	0.02	1.39 × 10 ⁻⁷	1.32 × 10 ⁻⁸
	190	2.29	0.03	1.38 × 10 ⁻⁷	1.32 × 10 ⁻⁸
	200	2.30	0.03	1.37 × 10 ⁻⁷	1.31 × 10 ⁻⁸
HDPE	170	2.48	0.04	1.82 × 10 ⁻⁷	4.40 × 10 ⁻⁹
	180	2.50	0.04	1.81 × 10 ⁻⁷	4.30 × 10 ⁻⁹
	190	2.52	0.04	1.79 × 10 ⁻⁷	4.30 × 10 ⁻⁹
	200	2.54	0.06	1.78 × 10 ⁻⁷	5.00 × 10 ⁻⁹

