Journal of
Manufacturing and Materials Processing

MDPI

Article

A Scale-up of Energy-Cycle Analysis on Processing Non-Woven Flax/PLA Tape and Triaxial Glass Fibre Fabric for Composites

Gilles Tchana Toffe [1], Sikiru Oluwarotimi Ismail [1], Diogo Montalvão [2], Jason Knight [3] and Guogang Ren [1,*]

1 School of Engineering and Computer Science, University of Hertfordshire, Hatfield AL10 9AB, UK; toffegi2002@yahoo.fr (G.T.T.); s.ismail3@herts.ac.uk (S.O.I.)
2 Department of Design and Engineering, Faculty of Science and Technology, Bournemouth University, Bournemouth BH12 5BB, UK; dmontalvao@bournemouth.ac.uk
3 School of Mechanical and Design Engineering, Faculty of Technology, University of Portsmouth, Portsmouth PO1 3DJ, UK; jason.knight@port.ac.uk
* Correspondence: g.g.ren@herts.ac.uk; Tel.: +44-(0)1707-281075

Received: 28 August 2019; Accepted: 23 October 2019; Published: 1 November 2019

check for updates

Abstract: In the drive towards a sustainable bio-economy, a growing interest exists in the development of composite materials using renewable natural resources. This paper explores the life cycle assessment of processing of Flax fibre reinforced polylactic acid (PLA), with a comparison of glass fibre triaxial fabric in the production process. The use of hydrocarbon fossil resources and synthetic fibres, such as glass and carbon, have caused severe environmental impacts in their entire life cycles. Whereas, Flax/PLA is one of the cornerstones for the sustainable economic growth of natural fibre composites. In this study, the manufacturing processes for the production of Flax/PLA tape and triaxial glass fibre were evaluated through a gate-to-gate life cycle assessment (LCA). The assessment was based on an input-output model to estimate energy demand and environmental impacts. The quality of the natural hybrid composite produced and cost-effectiveness of their LCA was dependent on their roving processing speeds and temperature applied to both the Flax/PLA tape and triaxial glass fabrics during processing. The optimum processing condition was found to be at a maximum of 4 m/min at a constant temperature of 170 °C. In contrast, the optimum for normal triaxial glass fibre production was at a slower speed of 1 m/min using a roving glass fibre laminating machine. The results showed that when the Flax and PLA were combined to produce new composite material in the form of a flax/PLA tape, energy consumption was 0.25 MJ/kg, which is lower than the 0.8 MJ/kg used for glass fibre fabric process. Flax/PLA tape and glass fibre fabric composites have a carbon footprint equivalent to 0.036 kg CO_2 and 0.11 kg CO_2, respectively, under the same manufacturing conditions. These are within the technical requirements in the composites industry. The manufacturing process adopted to transform Flax/PLA into a similar tape composite was considerably quicker than that of woven glass fibre fabric for composite tape. This work elucidated the relationship of the energy consumptions of the two materials processes by using a standard LCA analytical methodology. The outcomes supported an alternative option for replacement of some conventional composite materials for the automotive industry. Most importantly, the natural fibre composite production is shown to result in an economic benefit and reduced environmental impact.

Keywords: Flax fibre; polylactic acid (PLA); renewable raw materials; triaxial glass fibre; energy consumption; carbon footprint; life cycle assessment (LCA)

1. Introduction

Natural fibre reinforced composites have attracted much interest from numerous industries during the last two decades, due to environmental concerns and cost-reduction requirements [1]. The attractiveness of natural fibres, as reinforcing materials with high specific strength, bio-degradable property and relatively low cost [2,3]. There are numerous studies that have focused on Flax fibre reinforced composites [4,5]. A noticeable increase in the sales volume of natural fibres, such as flax and matrices polylactic acid (PLA), has been reported in European and Asian markets in the building services, transportation (automotive, aerospace and marine/naval) and furniture industries [6–8]. In contrast to natural fibres, human-made glass and carbon fibre composites with conventional petroleum-based polymers, such as polyethene (PE), polypropylene (PP), and polyvinyl chloride (PVC), have negative environmental impacts during their cradle-to-grave and gate-to-gate life cycle [9].

Therefore, to design and fabricate a new composite with a lower environmental footprint, some new natural fibres and matrix are being considered for the significant reduction of their carbo-foot print, i.e., the Flax/PLA. Flax is one of the most promising natural fibres, because it is a renewable raw material, has excellent biodegradability and favourable mechanical properties, while PLA has good processability and can be readily fabricated to injection-moulded parts, film or fibre [10]. The combination of Flax/PLA also has desirable mechanical and processing properties, in addition to its adjustable biodegradation feature [11–13]. After being mixed with flax, the impact strength of the resulting Flax/PLA is significantly improved.

Life cycle assessment (LCA) is a sustainability measurement tool for environmental impact analysis that assists this work in terms of decision making in product development [14,15]. It has been used to investigate the inputs (resources and energy) and outputs (waste gases, wastewater and solid waste) of a product across the entire life-cycle stages (cradle-to-grave) [16–18]. The advantages of utilising LCA include, but are not limited to the absence of problem shifting from one life cycle stage to another, locates 'hot spots' in the life cycle and accounts for all types of pollutant emissions and resource consumptions [19].

Therefore, it covers the entire life cycle of a product, which includes five stages, acquisition of raw materials, processing/manufacturing, consumption/utilisation, transportation and waste disposal of the products [20]. In the process of gate-to-gate production, the specific manufacturing processes and the raw materials involved are considered to determine the energy consumption and carbon dioxide emissions of these processes alone. The gate-to-gate inventory includes three stages: Machine, energy used and manufacture of the products [21]. Accordingly, this analysis only included the inputs and outputs between the acquisition of raw material and manufacture of the products [22,23], which are more concise, convenient and appropriate to evaluate the gate-to-gate environmental impacts of composite materials. LCA has been associated with various design and processing technologies [24], relevant materials/products [25], decision making [26], waste management [27], and regional industrial ecology [28].

Furthermore, a few studies have considered comparative LCA of the energy consumption to produce materials and specific components made from glass (synthetic) fibre reinforced (GFR) and natural fibre reinforced (NFR) composite materials [29–37]. This is subsequently summarised with methodology and findings from the studies discussed.

Youngs et al. [28] studied LCA of fibre reinforced composites by reporting that, the first stage of the product life cycle is material extraction for plastics or similar materials, which involves pulling fossil fuels from the earth. 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, which is termed material production. Materials used in diverse fields have different energy intensities for extraction and production. 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 414,000 million MJ of energy consumption in the USA in 1998, which amounts to 2.2% of the total energy consumed by the USA [30]. Stiller [31] compared and analysed several manufacturers of glass fibres, including PPG, Owens Corning, and Vetrotex. Owens Corning consumed the lowest intensity of 12.58 MJ/kg, whereas Vetrotex had the most considerable intensity of 32.0 MJ/kg. Even within one of the manufacturers, energy intensities changed significantly: Vetrotex plants in Germany consumed 32.0 MJ/kg, while Vetrotex International Plants used 25.3 MJ/kg. This can be explained in part by economies of scale, because a lower energy consumption results from larger-sized plants, in this case allowing energy savings of about 20%.

On the other hand, energy consumption is roughly independent of the filament diameter of the glass fibres produced. The natural fibres, including China reed and flax fibres, have relatively low energy intensities, because they come from natural sources. However, there are other environmental impacts related to their cultivation, especially the use of land, water, fertilisers and pesticides [29].

Similarly, Wotzel et al. [32] presented life cycle assessments of a side panel for an Audi A3 car made from ABS co-polymer and an alternative design made from hemp fibre epoxy resin composite of 66% volume. Their models were used to study the inputs, energy use and emissions up to the component manufacturing stage. The use phase and end-of-life management options, such as energy recovery through incineration, are not considered in their research. For the natural fibre reinforcement (NFR) component, the cultivation of hemp, hemp fibre extraction and component manufacture stages are also not included in the analyses. In addition, Schmidt and Beyer [34] simplified LCAs of two designs of an insulation component for a Ford car. The reference component was made from ethylene propylene diene copolymer (EPDM), and polypropylene (PP) reinforced with glass fibres. They presented their final results only in the form of net benefits of switching to the hemp fibre component from glass fibre reinforcement (GFR) component. The hemp fibre component showed a net benefit of 88.9 MJ in increasing energy demand, 8.18 kg of CO_2 emissions, 0.0564 kg of sulphur dioxide emissions, 0.002 kg of phosphate emissions and 0.018 kg of nitrate emissions in the basic scenario.

Moreover, Vidal et al. [36] confirmed that the environmental impact potential (global warming, depletion of non-renewable energy resource, acidification and eutrophication) from the fibre reinforced polymeric composites was lower than that of virgin PP and high-density polyethene (HDPE). Bolin and Smith [36] found that the environmental impacts from lumber treated with alkaline copper quaternary (ACQ) were 14 times less than for fossil fuel use, almost three times less for greenhouse gas emissions, potential smog emissions and water use when compared with those from wood plastic composite (WPC) decking. Also, they reported four times less for acidification and almost half for ecological toxicity, whereas, for eutrophication, the environmental impacts were approximately equal. Xu et al. [36] found that considering the ecological impact, woven fibre reinforced polypropylene composites were superior to neat PP if material service density is used as the functional unit.

Based on extensive literature, it is evident that very few efforts have been made to evaluate the environmental impacts of the production of Flax/PLA tape composite (FTC) in comparison to that of triaxial glass fibre (TGF). The present paper considers the application of LCA methodology (gate-to-gate) to explore the possibility of promoting eco-efficiency of FTC and triaxial glass fibre (TGF). Energy demand and potential environmental impacts of the FTC and TGF are investigated across its gate-to-gate stages. Then, the environmental benefits of the FTC are estimated across other materials after the mechanical properties, and environmental impact has been calculated.

This paper focuses on the evaluation of the environmental impacts of the Flax/PLA production process in order to assess their increased application as engineering materials in the near future. In this research work, Flax /PLA fibres were incorporated together at the PLA melt point to form a non-woven fabric as a Flax/PLA composite tape (FCT) through a hot-press laminating process technique. Hybrid FCT has not undergone any consolidation processing before the composite is formed. The operating parameters, such as Flax/PLA fibre content, temperature and speed, have significant influences on the production performance of composites material Flax/PLA tape. The results have proven that FCT direct forming is an efficient and cost-saving method of making fibre reinforced composites, which are suitable for industrial production. An identification of the primary drivers of the relative environmental performance of natural fibre composite tape was carried out to find a conclusion on whether the specific findings can be generalised and commercialised.

2. Materials and Methods

2.1. Materials

The input energy consumptions of Flax/PLA tape and triaxial glass fibre were based on studies of a tape machine in Tilsatec and triaxial glass fibre woven-fabric machine in Formax. Tilsatec used purchased flax and PLA fibres from Europe (Belgium and France) to produce Flax/PLA composite tapes. Whereas, Formax used purchased glass fibre tows and transformed them into triaxial glass fibre fabrics. Based on the mechanical properties of both materials and melting points, to accurately assess the best quality of laminates, the Flax/PLA tape laminating temperature and processing speed were selected and optimised. During the manufacturing of Flax/PLA composite tape, three ratios of the Flax/PLA were selected for the production process, which was, 60/40, 50/50 and 40/60. The Flax/PLA fibre passed through a mixture of gear and cylindrical wheels to produce one Flax/PLA composite tape. The manufacturing process to produce triaxial glass fibre fabrics was using the glass fibre tows by weaving and stitching them at a constant thickness. SimaPro 8 and eCoinvent was used to measure and produce some of the primary and secondary data.

The manufacturing process of composite material uses specific machines to transform flax and PLA fibres, and glass roving into fabrics for composite materials. Both the tape machine and Triaxial machine during productions require the purchasing of electricity. In addition, the processes used to require the purchase of flax and PLA fibres or glass tows for the productions of both Flax/PLA composite tapes and triaxial fabrics. The gate-to-gate (GtG) processes, as shown in Figure 1, have been used in this research to assess production as tree processes to find out the energy consumptions and environment impacts of the two targeted productions.

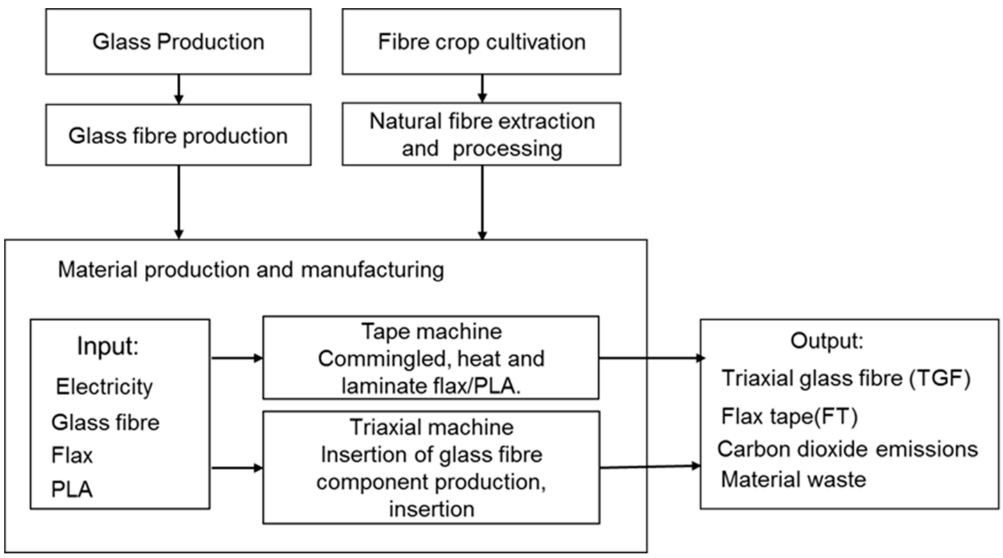

Figure 1. System boundaries of composites Flax/ polylactic acid (PLA) tape manufacturing process and triaxial glass fibre (TGF) reinforced composites production process [38].

2.2. Methods

The model of this study was constructed using SimaPro 8, a commercial LCA software product, to produce the process trees and to use weighted values to translate a recorded inventory into the potential impact on the environment. The measurement methodology consists of using a monitor to record domestic electricity usage to compile targeted gate-to-gate (GtG) data for the project. During the data collection process, a current sensor is clipped on to the supply cables on the machine connected to the transmitter, which then wirelessly sends real-time data to the energy monitor. The monitor receives the data and displays in kilowatts consumed at any given time, as shown in Figure 2.

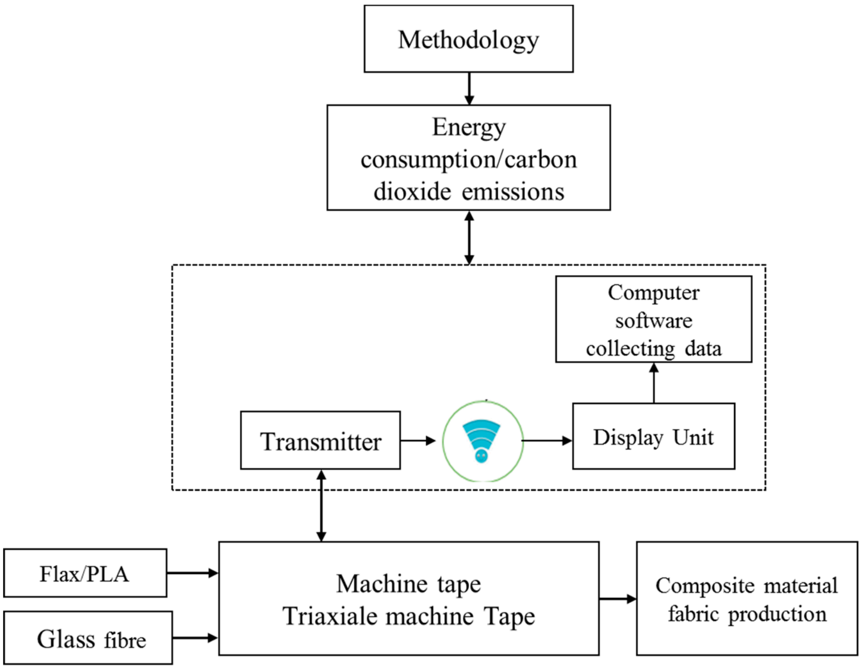

Figure 2. Gate-to-gate (GtG) based on data collection on the production process stage of Flax/PLA.

Thereafter, the data collecting system exports the data and save the data to a converting device, named eLink 2.0 (eCoinvent computer software). The electricity used in kWh or Megajoule (1 kWh = 3.6 MJ or 1 MJ = 0.277778 kWh) during the materials processing is then converted into equivalent CO_2 (carbon dioxide) production in kg using conversion factors 1 for Impact assessment [39], and 0.523 for electricity [40]. For example, if a 1000 kWh unit of electricity is consumed in the production of 6500 kg of Flax/PLA tape composite, the amount or quantity of equivalent CO_2 emissions can be calculated 523 kg·(CO_2) by using the conversion factor for electricity 0.523 [40].

Table 1 shows the methods used to collect energy on the machine during the transformation of the raw materials into the fabric. This process provides some of the direct energy consumptions 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, as shown in Figures 3 and 4. Thereafter, the data can be used to estimate the cost, CO_2 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.

Table 1. Energy consumption for various materials and processes.

Materials	Energy Intensity (MJ/kg)	CO_2 Emissions (kg CO_2)	References
Glass fibres	13–32	1.8–4.6	[28]
China reed fibres	3.6	0.5	[28]
Flax fibres	6.5	0.9	
	Process analysis		
Fibre production	12.24	1.7	[28]
Fabric production	0.772	0.1	[31]
Prepreg production	40.0	5.8	[31]
Resin production	34.2	4.9	[31]
Flax tape fabric	12.25	1.7	Source: Tilsatec
Triaxial glass fabric	29.04	4.2	Source: Formax
Glass fabrics manufacturing	30.84	4.5	[31]
	Prepreg material production		
Prepreg flax tape component	64.49	9.3	Source: Tilsatec [31]
China reed fibre-epoxy	56.61	8.2	[41]
Glass fibre-epoxy	83.84	12.18	[41]
Triaxial glass fabric-Epoxy	82.04	12	Source: Formax [41]

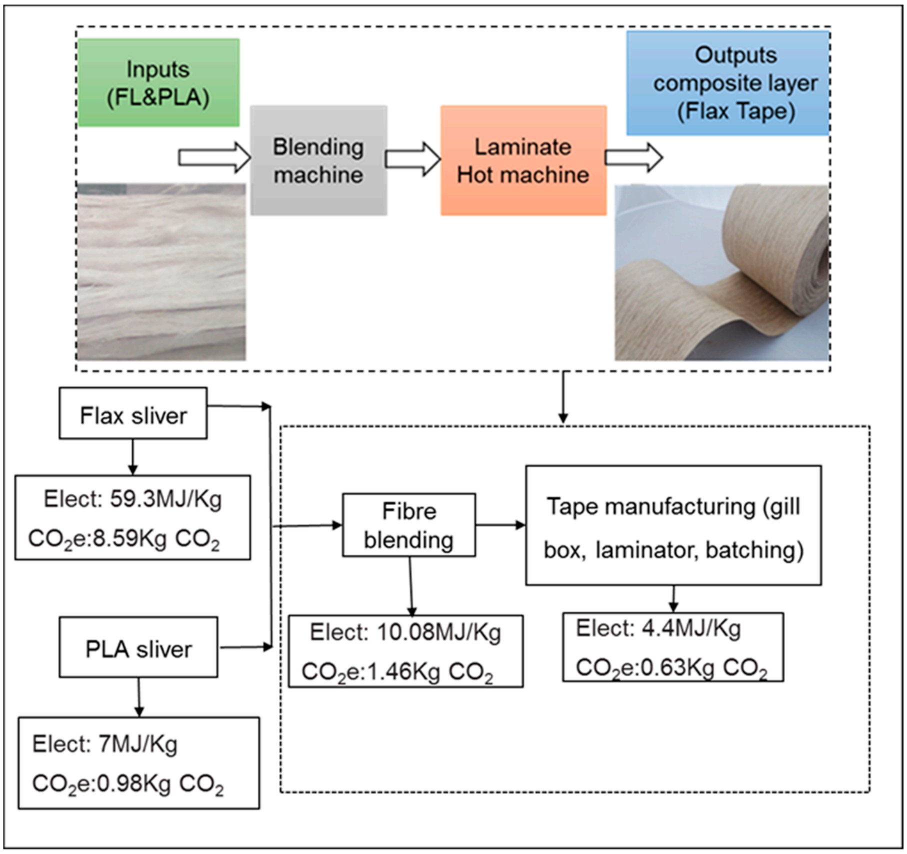

Figure 3. System boundaries of composites Flax/PLA tape manufacturing process.

2.2.1. Prediction Method to Calculate the Energy Consumption and Environment Impact

The primary objective of the manufacturing processes is to transform raw fibrous materials into useful final composite products for use in the automotive industry. It is also desirable to achieve a reduce panel weight, with lower energy and lower carbon-footprint of the natural material resources.

During these processes, the material resources used can also be changed, so creating new composite materials with less energy consumed.

Several studies have focused on estimating the energy consumption of various production processes. However, in a comprehensive study on the energy consumption of manufacturing processes developed by Duflou et al. [42], most of the available databases are incomplete, because they are limited primarily to the theoretical calculation of energy consumption. The study of energy consumption in various industrial processes has focused on different aspects: The development of energy consumption, indicators and power estimation models for several materials and manufacturing processes. The performance of manufacturing equipment or machines in this database is compared with respect to energy consumption losses, in particular for injection moulding technology [43]. We have assessed the energy efficiency of several manufacturing processes [39], which include the data collected from new tools, heating methods, and the efficiencies of the processes [39]. All of these energy efficiency data are used to support the derivatives in this research.

2.2.2. Calculation Method for Life Cycle Energy Consumption

Information of raw materials has been obtained from literature, as well as data gathered directly from manufacture processes at Tilsatec, a PLA fabric producer, and Formax Ltd., a glass fibre fabric producer, both of which are in the UK. In this paper, the material production processes were compared using the adapted LCA methodology. Generally speaking, to calculate the life cycle energy consumption of composite products, the energy, *E* (input) in kilowatt-hours (kWh) per day consumed is equal to the power, *P* in watts (w) times number of usage hours per day, *T* divided by 1000 watts per kilowatt [44].

In order to find out the energy consumption in kWh during the manufacturing process for the specific machinery, information about the production time and the number of voltage and ampere are needed based on Equation(1) [44]. The voltage and ampere can be found on the motor logging used for the specific process for energy, and CO_2 consumption calculation is shown as Equations (1) and (2).

$$E\left(\frac{kWh}{day}\right) = P(W) \times \frac{t\left(\frac{h}{day}\right)}{1000\left(\frac{W}{kW}\right)}, \tag{1}$$

$$E\left(\frac{kWh}{day}\right) \times\ CF\ (kg\ CO_2\ /kWh) =\ kg\ CO_{2e}, \tag{2}$$

where *E* is the energy in kWh/day, t is the time in hours/day, and *P* is the power in Watt, which is the product of voltage, V (v) and current, I (A).

The environmental impact can be characterised by the conversion of these outputs. Therefore, the electricity used in kWh or Mega Joule (1 kWh = 3.6 MJ/kg) can be converted into kg of carbon dioxide by using the conversion factor(CF) [45]. Other factors, such as heat, waste of material and global warming concerns, are not considered in this paper in order to simplify the analysis.

Also, according to the rules in global warming potential (GWP), the impact contribution of a product can be calculated by multiplying the number of emissions by the impact assessment factor [46]. The GWP has been developed to promote a comparison of the global warming impacts of different emission gases [34]. Specifically, the GWP is a measure of the emission energy that would allow one tonne of CO_2 gas to be absorbed over a given period. Therefore, direct global warming potentials (GWP) is expressed as [47]:

$$\mathrm{GWP} = \sum \mathrm{CO_2}\ \times\ \mathrm{IAF}. \tag{3}$$

Hence, the inventory analysis provides emission data in the unit of kg as a functional greenhouse gas emission that can be converted into an equivalent amount of carbon dioxide (kg CO_2 eq.) generation using a GWP. In this example calculation of a characterisation factor, global warming potential (GWP) is presented in terms of equivalent emissions of carbon dioxide (CO_2) using units of kg of carbon dioxide equivalents (kg CO_2 eq.) [47].

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, CO_2 GWP = 10 kg × 1 = 10 kg CO_2 eq.
CO_2 methane = 5 kg × 23 = 115 kg CO_2 eq.

The global warming potential to produce glass fibre filament winding can be calculated to show a higher environmental impact of a product during its production, therefore, being able to choose other alternative materials that 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 [47].

2.3. Manufacturing Process

2.3.1. Manufacturing Flax/PLA Tape

Materials and manufacturing processes of Flax and PLA deal with issues that may lead to better utilisation of raw materials and energy, integration of design and manufacturing activities. The fabrication process for Flax/PLA tape necessitates a systematisation and control of the speed, which was optimised and set at 4 m/min. The temperatures are also adjusted to 170 °C to obtain a high-quality composite reinforcement Flax/PLA tape.

During the single process of blending and laminating, the amount of electricity used is logged and later converting to CO_2 emissions. The process consists of passing the materials polylactic acid and Flax fibre (Flax/PLA) through a prepregging machine to transit the blending inputs to be fully thoroughly mixed and unidirectional aligned. They move through a hot cylindrical wheel, which is connected to a laminator at an elevated temperature of 170 °C that transformed the raw materials to composite Flax/PLA tape as schematically illustrated in Figure 3. Within the process, long fibres of Flax fibre bondless and unidirectional PLA fibre ravings are used in the machining process to form a continuous laminating Flax/PLA tape. The processes are simple, but they produce some shrinkage on Flax/PLA tape during production.

The manufacturing of 6.7 m^2 of composite Flax/PLA tape weighs approximately 1 kg. For one-hour laminating production, approximately 35.8 kg of composite Flax/PLA tape can be produced. The advantage of this laminating process is the yielding of composite material tape that can be used for fabrication of the complex component for the automotive industry. Consequently, the typical processes for the final composite products using Flax/PLA tapes include vacuum infusion (VI), and resin transfer moulding (RTM). This composite tape product can also be further impregnated, as well as carried out in the same way as some of the glass fibre composite processes. Compared to glass fibre composites, flax offers reduced weight, improved environmental impact, better vibration damping and less thermal transmission or thermal protection with, retained specific stiffness and is safer to handle.

If 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 weights of the fibre from Equation (4) and then finding the mass of each type of fibres,

$$W_{Flax} + W_{PLA} = W_{comp(Flax/PLA)}. \tag{4}$$

The theoretical approach to calculate energy consumption can be expressed, as shown in Equation (1). The resource, activity and emissions of GtG are limited in a single process as discussed previously in composite Flax/PLA laminating. Therefore, the three phases of life, are seen as a self-contained unit, with notional “gates” through which inputs pass through, and outputs emerge from. Depending on the mechanical properties, this research selected three different ratios in Flax/PLA compositions for comparison.

2.3.2. Manufacturing Triaxial Glass Fibre

The manufacturing process for triaxial glass fibre runs at a slower speed setting when compared to Flax/PLA fibre in order to produce good quality with smooth textures and structure at the same fabric grammage. The average amount of electricity is shown in Figure 4, which is obtained at each stage of the manufacturing process. This represents the production of the raw materials from glass silica sand and borate to produce unidirectional (UD) glass fibres. The electricity used was converted to the CO_2e that was deducted from their energy consumption, which was used in transforming glass fibre roving/yarn to triaxial fabrics. The average electricity usage depends on the machine set up and speed (at 1 m/min). 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 in Wakefield, UK. The three-layer glass roving fibre is laid down at −45°, 90° and 45° and then lightweight stitching holds these fibres together and parallels in each layer.

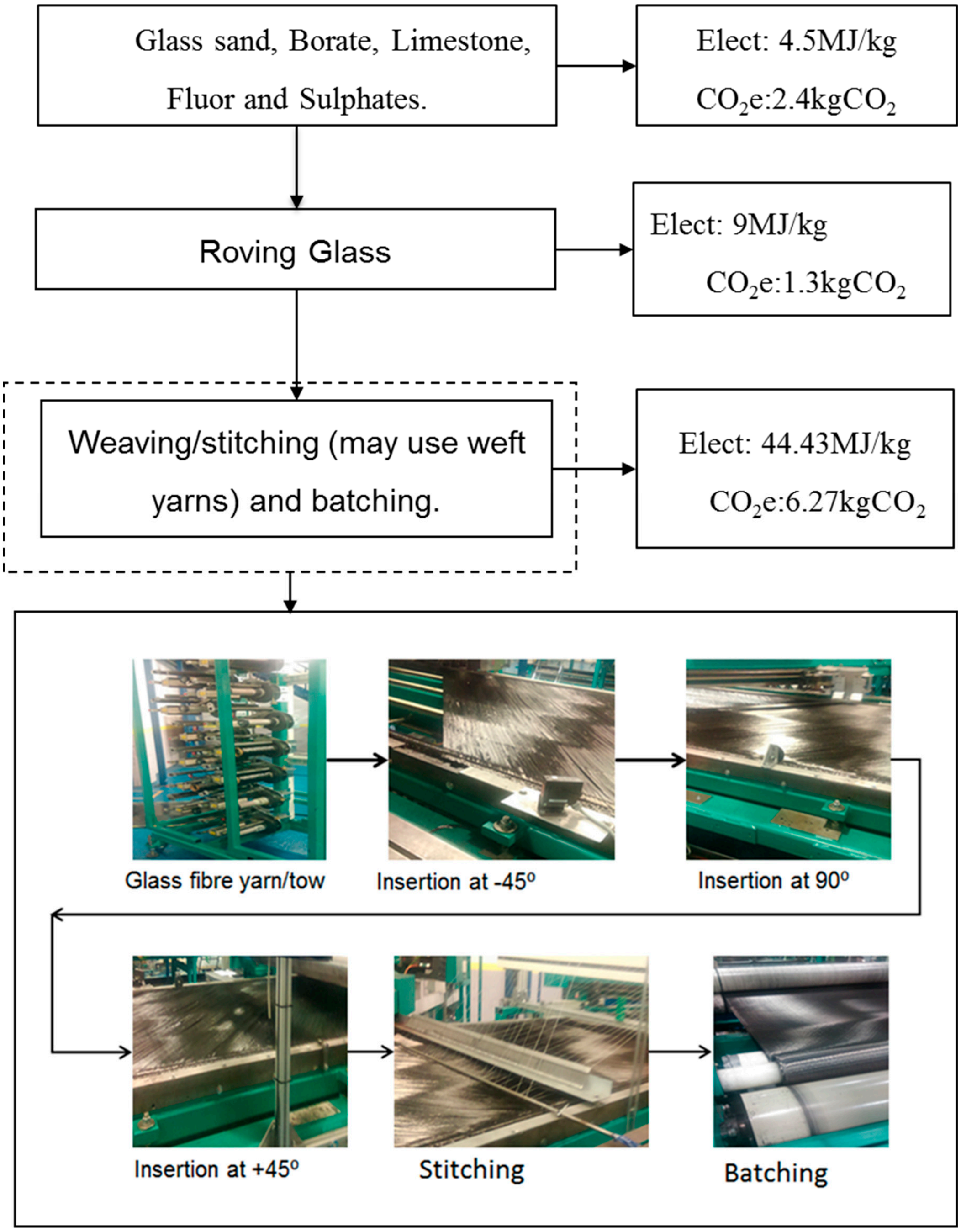

Figure 4. System boundary manufacturing process of multiaxial glass fibre to produce structure fabrics at Formax.

When manufacturing multiaxial glass fabrics, the glass fibre roving is sewn together layer-wise and forms a slide proof. The electricity consumption varies from one process to another, mainly depending on the running speed of the machine in the process.

3. Results and Discussion

This work used data, which was collected to model material flow, energy use, emissions and environmental impacts in all the manufacturing stages, without considering inventory and assessment, as shown in Figure 1. These simplified manufacturing process stages are made from glass fabric and natural fibre Flax/PLA composites.

The system boundary and the process used for producing triaxial glass fibre (TGF) and Flax/PLA tape are shown in the transformation of flax, and PLA into composite material fabrics (two materials combine into one material) and glass fibre into fabrics. The environmental aspects and potential impacts, throughout a products life from raw material production and extraction through production, were not considered in this study. With the production of a range of laminate mixed composite material, some theoretical expressions have been adopted to define the percentage of each composite material. The volume fraction of the composite material, V_c and the sum of the amount of each material are determined based on Equation (5),

$$\%\ Wc \times \ell_{flax} + \%\ Wc \times \ell_{flax} = W_c. \tag{5}$$

The weight of the composite material flax and PLA $W_{comp(Flax/PLA)}$ was determined by Equation (4), from the weight ($W_{\text{flax or PLA}}$) of the fibre/PLA to obtain the density ($\ell_{\text{flax or PLA}}$) of fibre/PLA and the total weight (Wc) of the composite materials. For example, if a Flax/PLA tape consists of 60% Flax and 40% PLA, we can produce 10 kg of composite tape with 6 kg of flax and 4 kg PLA.

3.1. Energy Consumption Profile

3.1.1. Energy Consumption during Production of Flax/PLA Tape

Within this study, the machine work for producing Flax/PLA tape was used to measure the energy consumption during the production; all associated tasks were timed for making a comparison between two processes for producing Flax/PLA and glass fibre fabrics in terms of the environmental impact. The energy consumption data was collected and calculated per hour and represented by different colours. However, the heat loss was not considered. In order to achieve these, the energy collection device was connected to the input (electricity and material) of the machine before the production started, for recording their energy consumption during the production of one batch (Figure 5).

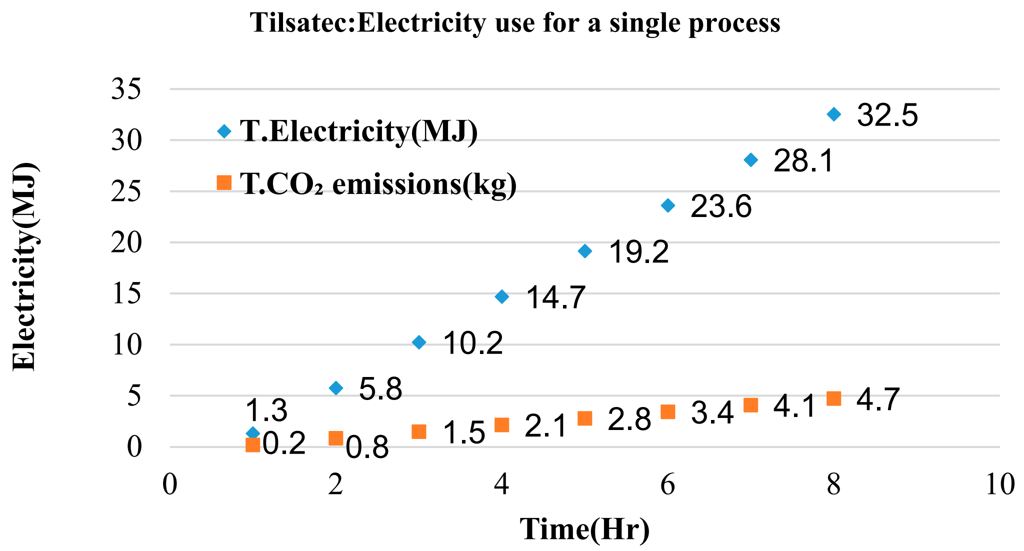

Figure 5. Daily electricity uses by Flax/PLA composite tape machine during a single manufacturing process (Tilsatec).

Comparatively, the higher data points represent the energy consumptions, and the lower data points represent the CO_2 emissions. It was evident that the electricity used at the end of production was determined to be 4.46 MJ/h with associated carbon dioxide emissions of 0.65 kg. The production rate was estimated at 18 kg/h equivalent to 0.25 MJ/kg for flax/PLA composite tape. The primary data on the test compared to the secondary data from LCA simulation by software (SimaPro 8), is shown in Figure 6. These are similar due to the lower environmental impact on the production of the Flax/PLA tape. Therefore, the energy consumption for a day in production for the Flax/PLA is estimated at E = 32.5 MJ/day for approximately 286.4 kg.

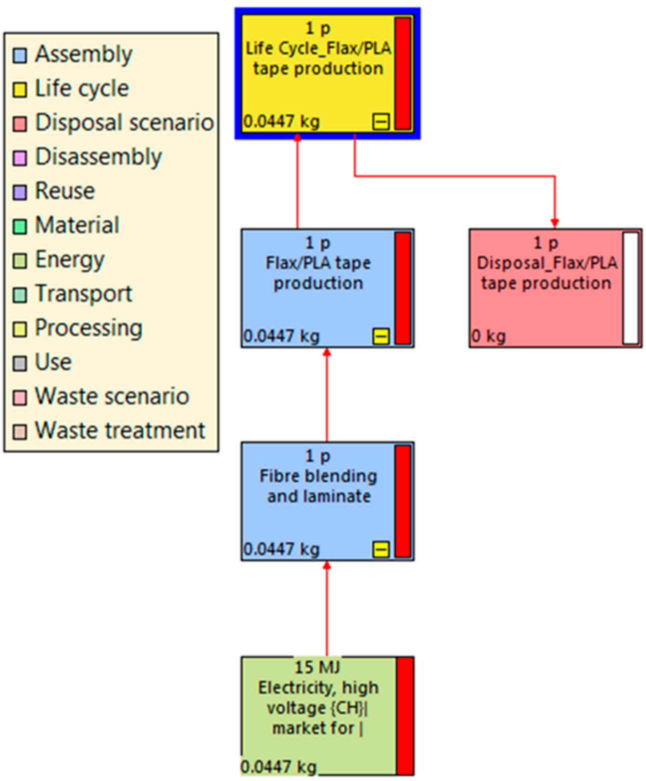

Figure 6. SimaPro 8 LCA simulation for the production of Flax/PLA tape.

The simulation of Flax/PLA for one process (1p) show the energy inputs of Flax/PLA tape, and the environmental impact is evaluated and illustrated in Figure 6. Each square is identified by a colour. The yellow colour indicates the LCA of the whole process and light blue indicates the assembling of both materials. The energy is indicated by light Beige, as shown in Figure 6 and Figure 8, for both material's production systems. The red column shows the thermometer of the manufacturing process. For example, fibre blending, and laminating cost 0.0447 kg of carbon dioxide, in the production for this process. The simulation shows that the process produced lower CO_2 emissions, by less than 1% in the total production of the Flax/PLA composite tape. The pink column on disposal of the tape showed that there was an environmental impact associated.

3.1.2. Energy Consumption during the Production of Triaxial Glass Fabrics

The energy consumption of triaxial glass fibre fabrics was estimated using conventional devices eCoinvent software (eLink). During the manufacturing of the triaxial glass process, the devices were set up on the input of the production machine and all-glass roving was uploaded on a rail system, as shown in Figure 2. The production of the glass fabrics used a low speed of 1 m/min to achieve a better consolidation of fabrics for the required quality.

The daily electricity used for the single process during the manufacture of glass fabrics is presented in Figure 7. There, the production rate was set approximately 0.5 kg per minute, 30 kg/h, which was equivalent to 0.8 MJ/kg of triaxial glass fibre fabric. The electricity consumption is estimated at 23.76 MJ/h, and CO_2 emission is at 3.45 kg. Daily energy consumption is estimated at 168.38 MJ/day with a carbon dioxide emission of 24.5 kg CO_2e. The production rate is approximately 0.5 kg per minute, 30 kg/h equivalent to 0.8 MJ/kg of triaxial glass fibre fabric.

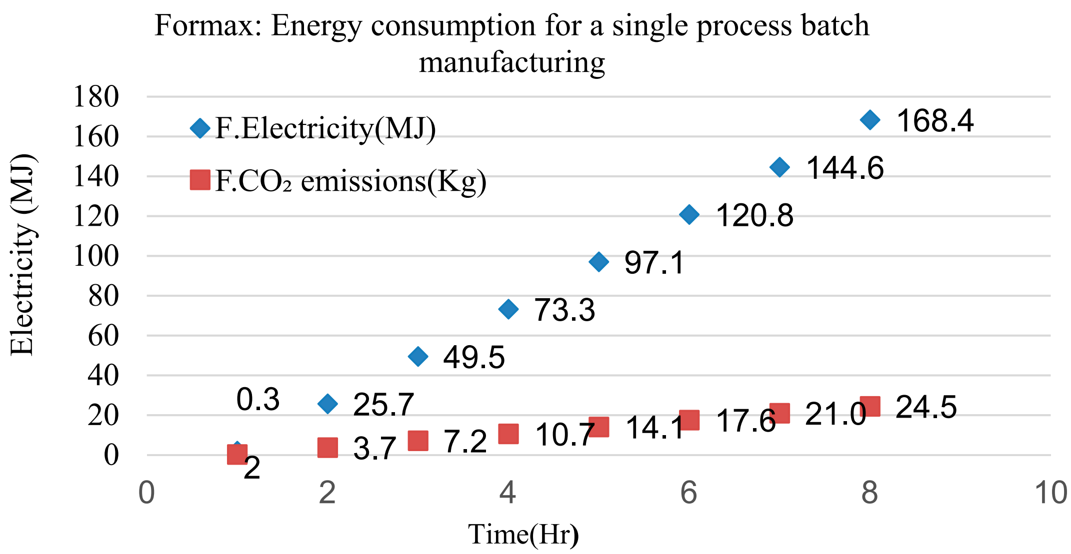

Figure 7. Daily energy consumption and CO_2e of triaxial glass fibre fabric in the targeted manufacturing process.

Since the energy intensities of materials vary, depending on the methods and infrastructure, there was a wide range of values collected, as shown in Table 1. For example, glass fibre, which is one of the most common materials used to reinforce plastics, has a broad production energy intensity. Hence, SimaPro 8 simulation has been used for simulation to produce the triaxial glass fabric to assess their energy inputs and environmental impact, as shown in Figure 8. While its process tree of the simulation is represented by a different colour, the process tree generated energy consumption, and automatically, the thermometer was represented in red for the carbon dioxide emissions. The simulation gave that the process produced a low CO_2 emission, which was less than 1% of overall CO_2 in the whole process.

The Pink column on disposal of the fabric showed that an environmental impact of glass fabric has been minimal and neglected.

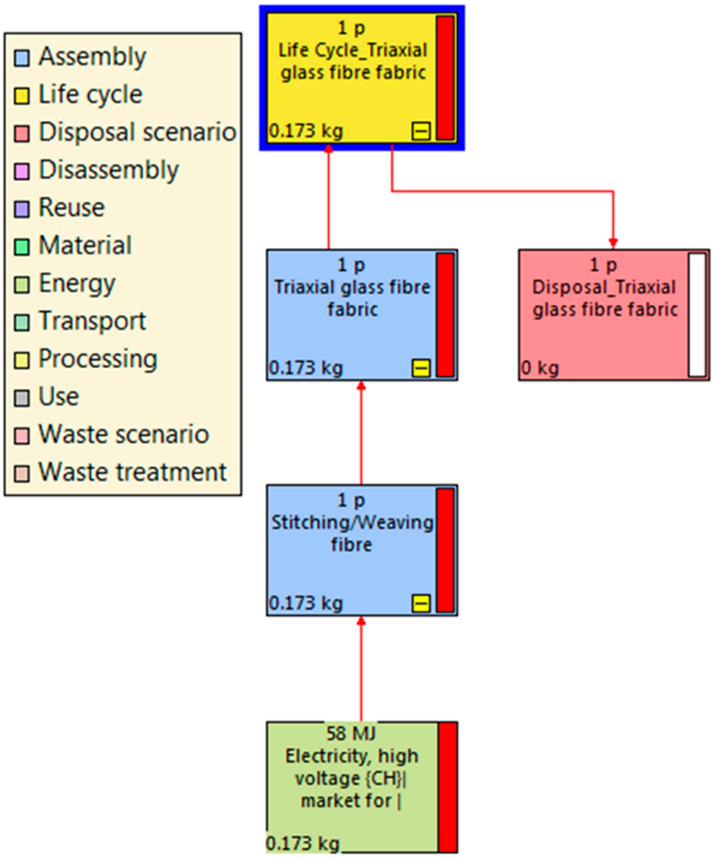

Figure 8. LCA SimaPro 8 simulation for the triaxial glass fabric production process.

In this method, the environmental impact is evaluated using only one process (1p), incorporating the energy inputs of triaxial glass fabric. The simulation showed that the thermometer in red generates 0.173 kg CO_2. The simulation also predicted the process produced CO_2 emissions of around, less than 1% of overall emissions associated with the production of the products. The light red column on disposal does not have any negative impact on the environment, as indicated in Figure 8.

The contributions for each manufacturing process are deduced and presented in Figure 9. The reproductions from GtG are shown in Figures 6 and 8. The results showed a lower carbon dioxide emission of the material production of composite materials tape and glass fabric over any of other processes involved in the overall production chains, which consisted of stitching, weaving, blending, melting and laminating to produce one composite material for industrial applications. The energy consumption can be high with a lower quantity of material production depending on the machine used to produce this material.

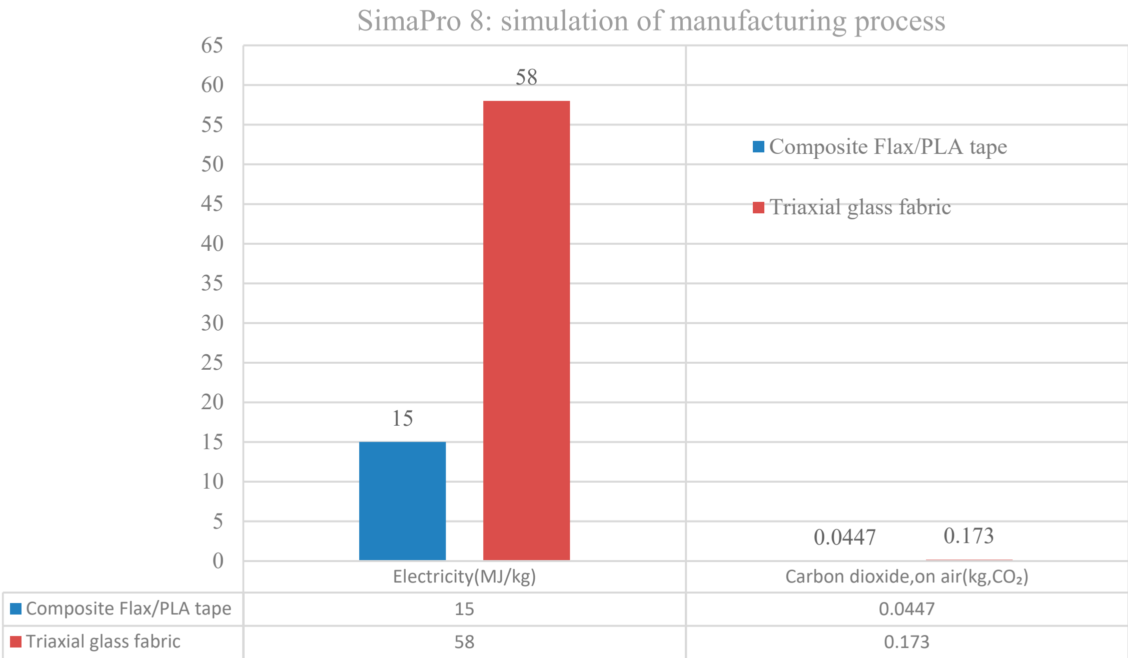

Figure 9. The simulation result of the SimaPro 8 simulation for the production of composite materials.

In addition, Table 1 indicated that process energy for the production of 1 kg. Flax/PLA tape needed is 12.25 MJ, while to prepare 1 kg of glass fabric is 64.49 MJ. Therefore, it is interesting to note that glass composite materials need higher energy intensity from the production. Furthermore, a lower air emission was achieved with a difference of 0.8% between prepreg Flax/PLA tape and china reed fibre. The energy consumptions to manufacture similar flat sheets (250 × 250 × 2.2 mm^3) and fibre/matrix ratio with different materials are shown in Figure 10. The comparisons illustrated that Flax/PLA tape generated 2.12 Kg/CO_2, and the total energy was estimated at 14.48 MJ/kg. This is compared with higher energy estimated at 116.43 MJ/kg and CO_2 generate of 16.66 kgCO_2 for production of a Glass/PP [46]. Therefore, the energy and emissions are considerably much less to produce the composite of Flax/PLA.

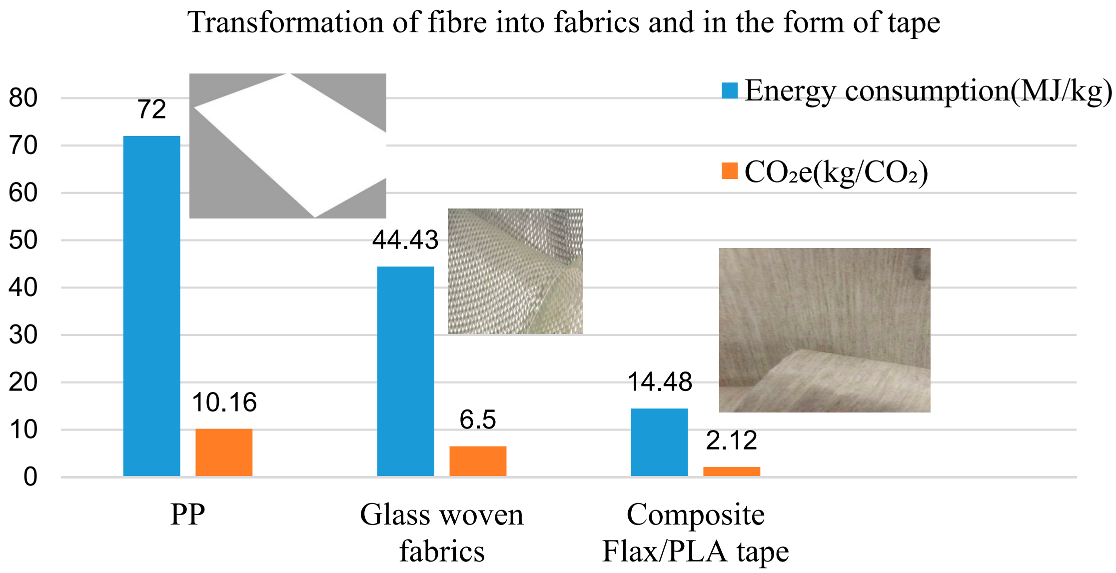

Figure 10. Energy consumption to produce fibre for composite materials.

The total mass of each of the composite materials is estimated at 2.05 kg and 2.90 kg for flax/PLA tape and glass/PP, respectively. Here we assume that the volume fraction of fibre is 40% flax/PLA tape and glass/PP 45% glass and 40%(PP).

3.1.3. Environment Impact of the Production of Composite Fabrics

The environmental impact potential is the weighted sum of the product of individual pollutant emissions and their individual characteristic 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 [47].

For the production of Flax/PLA tape, the operations involved, heating, blending and laminating on the tape machine to produce the final product. The total energy consumption of fibre blending and tape manufacturing, in its gate-to-gate phase, is estimated at 15 MJ/kg with associated carbon dioxide emissions of 0.0447 kg/CO_2. As long as the production of Flax/PLA tape fulfils the aesthetic expectation and the dimensions are met, the targeted process for Flax/PLA tape has succeeded with lower energy consumption compared to other composite fibre systems, such as glass fibres. Moreover, the energy consumed to produce triaxial glass fibre fabric can alternatively be used to produce 40% more composites using Flax/PLA tape. The power energy needed for both cultivation and transportation was not considered for the harvest of flax environmental impact on water and the earth.

In addition, the life cycle assessment impacts for the production of Flax/PLA tape and triaxial fabric; are with low emissions on the environment based on the eco-indicator 99 weightings, depending on the sum of materials produced, as shown in Figures 11 and 12. The production of composite material shows the different area of environmental impact depending on the type of composite material selected; For example, the impact on 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. A high amount of composite material, with lower environmental impact, can also provide less impact on the environment during its production.

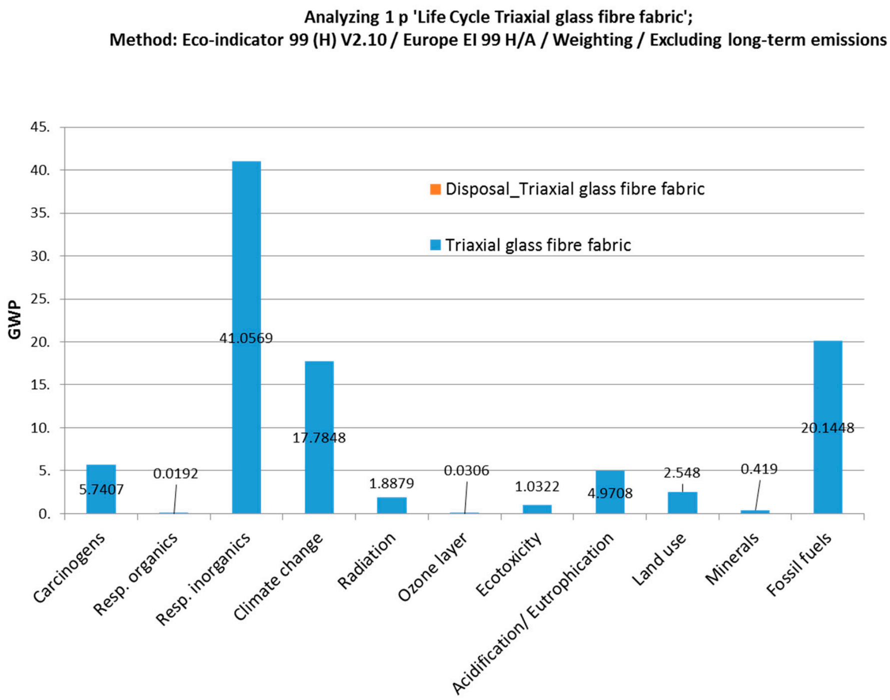

Figure 11. SimaPro 8: Environment impact of triaxial glass fibre fabric overall environment coverage.

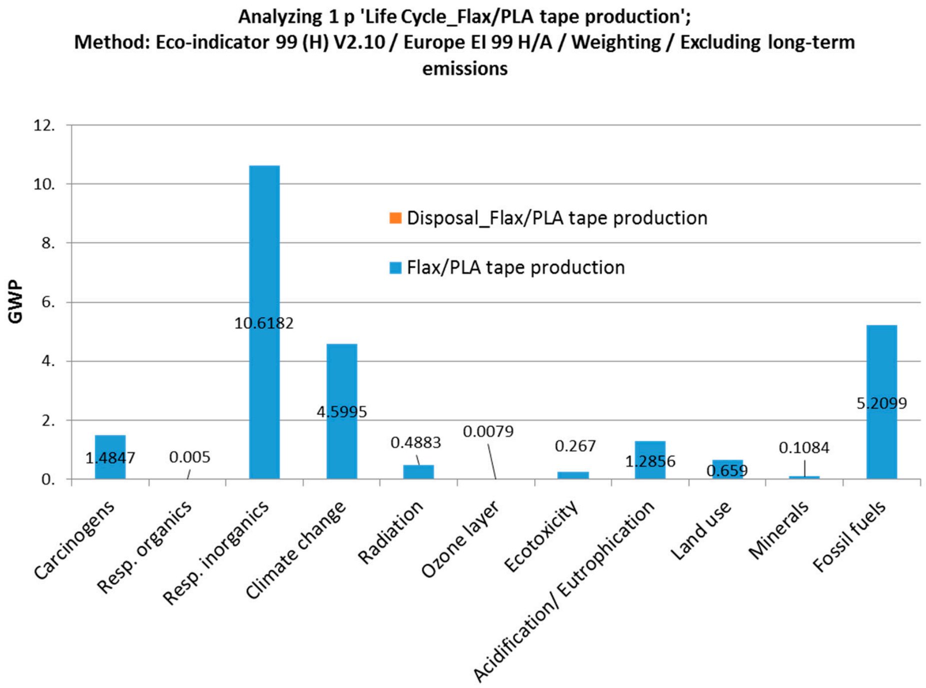

Figure 12. SimaPro 8: Environment impact of composite Flax tape overall environmental coverage.

In contrast to human-made materials, the production of natural plant fibre requires natural resources. Therefore, the water emissions of nitrates, phosphates and nitrogen oxide (NOx) into the air are higher compared to human-made materials, because of fertiliser applications in growing Flax. For example, in epoxy-based natural fibre composites, as listed in Table 2, we found that the environmental impacts for the natural fibre composite are still dominated by the energy and emissions from epoxy production. Even though natural fibre accounts for 66% of the volume of the component, it only contributes 5.3% of the cumulative energy demand [32]. The Flax/PLA composites have overwhelming environmental advantages over their counterparts in relation to the energy demand the environmental impact load, water consumption and solid waste. Nevertheless, the LCA 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 depend on subjective expert opinion. On the other hand, the gate-to-gate assessment of the Flax/PLA tape does not include the product use and end-of-life phases, which limits the ability to identify the burden-shifting.

Table 2. Environment impact to produce flax tape compare to glass fibre [42].

Environmental	Glass Fibre Pallet/PP	Triaxial Glass Fabric-Epoxy	Natural Fibre Reed /PP	Flax/PLA Tape
Total energy use (MJ/kg)	70	82.04	35.7	15
Carbon dioxide emissions (kg)	3.65	4.27	2.1	1.38
Carbon monoxide (g)	3.71	4.34	2.73	0.0447
NOx (oxides of nitrogen) air emissions (g)	25.65	30	17.45	NE
Sulphur oxides (SOx) air emissions (g)	14.45	17	8.15	NE
Water emission—BOD (mg)	20.7	24.35	13.3	1.32
Water emissions—nitrates (g)	0.086	0.1011	7.65	NE
Water emissions—phosphates (g)	0.029	0.0341	0.08	NE
CML—Greenhouse effect (kg CO_2 eq.)	3.76	4.42	2.02	NE

NE denotes not estimated.

It was clear that boundary selection had a significant influence on the gate-to-gate (GtG) observed results. In this study, the manufacturing requirements monitored the purchased electricity to produce use of Flax/PLA and triaxial glass fibre. The consumption of electricity leads to energy consumption and carbon dioxide generated based on the new ISO standards 14,040 to 14,043.

The results showed that PLA, as a matrix material for composite, combines well with Flax/PLA, is cheaper to produce, and the processing technique is not as complicated as other conventional products. The process of commercial production of tape composites is promising based on the manufacturing process and the reduced environmental impact. However, there are significant differences regarding the specific component/application being studied. This is also affected by production processes, the data sources used, the environmental impacts considered, as wells the boundaries and scope of the life cycle assessment. However, some care is needed in interpreting the LCA results of the fibres and their composite. Product comparisons across alternatives or substitute products are meaningful only when the same methods and system boundaries are used to derive the results. The repercussions of comparing natural fibre to synthetic fibre could lead to significantly flawed conclusions. Hence, future research should focus on achieving equivalent or superior technical performance and component life towards specific mechanical properties in targeted applications. The energy consumption of each process has been recorded following similar production processes. The environmental impacts of the Flax/PLA have shown fewer processing steps to transform the raw materials into the composite Flax/PLA tape with less energy consumption and lower carbon dioxide emissions from production when compared to synthetic glass fibre fabric production.

4. Conclusions

This investigation provides useful information to the manufacturing, processors, consumers and policymakers of sustainable composites materials using Flax/PLA tape as a raw material. The eCoinvent link and SimaPro 8 was used to evaluate the manufacturing process and analyses the energy consumption and environmental impact of the production of composite material fabrics and triaxial glass fabric. Our life cycle assessment was carried out to estimate the energy consumption for producing two types of composite materials: Flax/PLA tape and triaxial glass fibre fabrics for intended use in the automotive industry. An efficient novel method has been used to record the energy consumptions of both composites during the manufacturing processes of these materials during their batch productions. The energy consumption is estimated at 0.25 MJ/kg for the production of Flax/PLA tape and 0.8 MJ/kg for triaxial glass fibre fabrics. The production of composite flax tape used less energy than the glass fibre and also some other materials already being used in the industry, such as carbon fibre for the composites. The energy consumption to produce a composite material using the prepreg process is estimated at 14.48 MJ/kg for Flax tape, 44.48 MJ/kg for glass fibre fabrics and 72 MJ/kg for polypropylene. From this study, natural fibre reinforced composites are environmentally superior to glass fibre reinforcement (GFR) composites on most LCA performance metrics. The results of this process showed improvement in the development of composite material and environmental impact.

Author Contributions: G.R., G.T.T., D.M. and J.K. designed the experiments. G.T.T., D.M. and G.R. performed the experiments. G.T.T. and G.R. wrote the initial paper. J.K., S.O.I. and D.M. did the proof reading, helped paper structural modification and revised English.

Funding: This research was supported by AMSCI, a Consortium Funding Scheme from BIS/Innovate UK and Birmingham City Council Reginal Growth Fund (UK), 2014-2017: Grant BIS/15/557- Advanced Manufacturing Supply Chain Initiative (AMSCI).

Acknowledgments: The authors sincerely appreciate the Tilsatec and Formax companies for their supports, to their facilities, premises and importantly, for the data collection. This work has been supported by the AMSCI Consortium Funding Scheme from BIS, 2014-17.

Conflicts of Interest: The authors whose names are listed immediately below certify that they have NO affiliations with or involvement in any organisation or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

References

1. Pickering, K.L.; Efendy, M.A.; Le, T.M. A review of recent developments in natural fibre composites and their mechanical performance. *Compos. Part A Appl. Sci. Manuf.* **2016**, *83*, 98–112. [CrossRef]
2. Van de Velde, K.; Baetens, E. Thermal and mechanical properties of flax fibres as potential composite reinforcement. *Macromol. Mater. Eng.* **2001**, *286*, 342–349. [CrossRef]
3. Garcia, M.; Hidalgo, J.; Garmendia, I.; García-Jaca, J. Wood–plastics composites with better fire retardancy and durability performance. *Compos. Part A Appl. Sci. Manuf.* **2009**, *40*, 1772–1776. [CrossRef]
4. Schirp, A.; Stender, J. Properties of extruded wood-plastic composites based on refiner wood fibres (TMP fibres) and hemp fibres. *Eur. J. Wood Prod.* **2010**, *68*, 219–231. [CrossRef]
5. Sykacek, E.; Hrabalova, M.; Frech, H.; Mundigler, N. Extrusion of five biopolymers reinforced with increasing wood flour concentration on a production machine, injection moulding and mechanical performance. *Compos. Part A Appl. Sci. Manuf.* **2009**, *40*, 1272–1282. [CrossRef]
6. Rajendran, S.; Hodzic, A.; Soutis, C.; MariamAl-Maadeed, A. Review of life cycle assessment on polyolefins and related materials. *Plast. Rubber Compos.* **2012**, *41*, 159–168. [CrossRef]
7. Nyambo, C.; Mohanty, A.K.; Misra, M. Polylactide-based renewable green composites from agricultural residues and their hybrids. *Biomacromolecules* **2010**, *11*, 1654–1660. [CrossRef]
8. Huda, M.; Drzal, L.T.; Misra, M.; Mohanty, A.K. Wood-fiber-reinforced poly (lactic acid) composites: Evaluation of the physicomechanical and morphological properties. *J. Appl. Polym. Sci.* **2006**, *102*, 4856–4869. [CrossRef]
9. Pickering, K.L.; Sawpan, M.A.; Jayaraman, J.; Fernyhough, A. Influence of loading rate, alkali fibre treatment and crystallinity on fracture toughness of random short hemp fibre reinforced polylactide bio-composites. *Compos. Part A Appl. Sci. Manuf.* **2011**, *42*, 1148–1156. [CrossRef]
10. Shah, D.U. Developing plant fibre composites for structural applications by optimising composite parameters: A critical review. *J Mater. Sci.* **2013**, *48*, 6083–6107. [CrossRef]
11. Corbière-Nicollier, T.; Laban, B.G.; Lundquist, L.; Leterrier, Y.; Månson, J.A.; Jolliet, O. Life cycle assessment of biofibres replacing glass fibres as reinforcement in plastics. *Resour. Conserv. Recycl.* **2001**, *33*, 267–287. [CrossRef]
12. Schmidt, W.-P.; Beyer, H.-M. Life Cycle Study on a Natural Fibre Reinforced Component. *Sae Trans.* **1998**, *107*, 2095–2102.
13. Diener, J.; Siehler, U. Ökologischer Vergleich von NMT-und GMT-Bauteilen. *Die Angew. Makromol. Chem.* **1999**, *272*, 1–4. [CrossRef]
14. Wötzel, K.; Wirth, R.; Flake, M. Life cycle studies on hemp fibre reinforced components and ABS for automotive parts. *Die Angew. Makromol. Chem.* **1999**, *272*, 121–127. [CrossRef]
15. Boustead, I. *Ecoprofiles of Plastics and Related Intermediates*; Association of Plastics Manufacturers in Europe: Brussels, Belgium, 1999.
16. Goedkoop, M.; Spriensma, R. *The Eco-Indicator 95*; PRé Consultants: Amersfoort, The Netherlands, 1995.
17. Guinée, J.G.; Heijungs, M.; Huppes, R.; Kleijn, G.; Wegener Sleeswijk, R.; Udo de Haes, A.; de Bruijn, H.A.; van Duin, J.A.; Huijbregts, R.; Huijbregts, M.A.J. *Environmental Life Cycle Assessment, An Operational Guide to the ISO Standard*; Draft Version; Centre of Environmental Science (CML), Leiden University: Leiden, The Netherlands, 2000; in prepare.
18. Jang, B.Z.; Ma, E.; Wang, C.J. Apparatus and Process for Producing Fiber Reinforced Composite Objects. U.S. Patent 5,936,861, 10 August 1999.
19. Duflou, J.R.; Kellens, K.; Guo, Y.; Dewulf, W. Critical comparison of methods to determine the energy input for discrete manufacturing processes. *Cirp Ann. Manuf. Technol.* **2012**, *61*, 63–66. [CrossRef]
20. Ribeiro, I.; Peças, P.; Henriques, E. Modelling the energy consumption in the injection moulding process. *Int. J. Sustain. Manuf.* **2015**, *3*, 289–309. [CrossRef]
21. Gutowski, T.G. The Efficiency and Eco-Efficiency of Manufacturing. *Int. J. Nanomanufacturing* **2010**, *6*, 38–45. [CrossRef]
22. Wang, G.; Zhao, G.; Li, H.; Guan, Y. Analysis of thermal cycling efficiency and optimal design of heating/cooling systems for rapid heat cycle injection molding process. *Mater. Des.* **2010**, *31*, 3426–3441.
23. Scacchi, C.C.O.; González-García, S.; Caserini, S.; Rigamonti, L. Greenhouse gases emissions and energy use of wheat grain-based bioethanol fuel blends. *Sci. Total Env.* **2010**, *408*, 5010–5018. [CrossRef]

24. China, S.; Mazzoleni, C.; Gorkowski, K.; Aiken, A.C.; Dubey, M.K. Morphology and mixing state of individual freshly emitted wildfire carbonaceous particles. *Nat. Commun.* **2013**, *4*, 2122. [CrossRef]
25. Dissanayake, N.P.; Summerscales, J.; Grove, S.M.; Singh, M.M. Energy use in the production of flax fiber for the reinforcement of composites. *J. Nat. Fibers* **2009**, *6*, 331–346. [CrossRef]
26. Ren, G.; Patel, H.; Hapuarachchi, D.; Crowther, S.; Fan, M.; Hogg, P.J. Development of natural HEMP fibre sheet mould composites (NF-SMC). In Proceedings of the 17th International Conference on Composite Materials, Edinburgh, UK, 27–31 July 2009.
27. Finnveden, G.; Hauschild, M.Z.; Ekvall, T.; Guinée, J.; Heijungs, R.; Hellweg, S.; Koehler, A.; Pennington, D.; Suh, S. Recent developments in life cycle assessment. *J. Env. Manag.* **2009**, *91*, 1–21. [CrossRef] [PubMed]
28. Song, Y.S.; Youn, J.R.; Gutowski, T.G. Life cycle energy analysis of fiber-reinforced composites. *Compos. Part A Appl. Sci. Manuf.* **2009**, *40*, 1257–1265. [CrossRef]
29. *ISO 14040:2006—Environmental Management–Life Cycle Assessment–Principles and Framework*; British Standards Institution: London, UK, 2006.
30. Pimentel, D.; Pleasant, A.; Barron, J.; Gaudioso, J.; Pollock, N.; Chae, E.; Kim, Y.; Lassiter, A.; Schiavoni, C.; Jackson, A.; et al. US energy conservation and efficiency: Benefits and costs. *Env. Dev. Sustain.* **2004**, *6*, 279–305. [CrossRef]
31. Stiller, H. *Material Intensity of Advanced Composite Materials: Results of Asudy for the Verbundwerkstofflabor Bremen Ev*; Wuppertal Papers; EconStor: Kiel, Germany, 1999.
32. Xu, X.; Jayaraman, K.; Morin, C.; Pecqueux, N. Life cycle assessment of wood-fibre-reinforced polypropylene composites. *J. Mater. Process. Technol.* **2008**, *198*, 168–177. [CrossRef]
33. Witik, R.A.; Payet, J.; Michaud, V.; Ludwig, C.; Månson, J.A.E. Assessing the life cycle costs and environmental performance of lightweight materials in automobile applications. *Compos. Part A Appl. Sci. Manuf.* **2011**, *42*, 1694–1709. [CrossRef]
34. Qiang, T.; Yu, D.; Zhang, A.; Gao, H.; Li, Z.; Liu, Z.; Chen, W.; Han, Z. Life cycle assessment on polylactide-based wood plastic composites toughened with polyhydroxyalkanoates. *J. Clean. Prod.* **2014**, *66*, 139–145. [CrossRef]
35. Vink, E.T.; Glassner, D.A.; Kolstad, J.J.; Wooley, R.J.; O'Connor, R.P. The eco-profiles for current and near-future NatureWorks® polylactide (PLA) production. *Ind. Biotechnol.* **2007**, *3*, 58–81. [CrossRef]
36. Alves, C.; Silva, A.J.; Reis, L.G.; Freitas, M.; Rodrigues, L.B.; Alves, D.E. Ecodesign of automotive components making use of natural jute fiber composites. *J. Clean. Prod.* **2010**, *18*, 313–327. [CrossRef]
37. Scharnhorst, W.; Althaus, H.J.; Classen, M.; Jolliet, O.; Hilty, L.M. The end of life treatment of second generation mobile phone networks: Strategies to reduce the environmental impact. *Env. Impact Assess. Rev.* **2005**, *25*, 540–566. [CrossRef]
38. Baumann, H.; Boons, F.; Bragd, A. Mapping the green product development field: Engineering, policy and business perspectives. *J. Clean. Prod.* **2002**, *10*, 409–425. [CrossRef]
39. Specification, P.A. Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. *Bsi Br. Stand. Isbn* **2008**, *978*, 580.
40. Wagner, B.; Svensson, G. A framework to navigate sustainability in business networks: The transformative business sustainability (TBS) model. *Eur. Bus. Rev.* **2014**, *26*, 340–367. [CrossRef]
41. Joshi, S.V.; Drzal, L.T.; Mohanty, A.K.; Arora, S. Are natural fiber composites environmentally superior to glass fiber reinforced composites? *Compos. Part A Appl. Sci. Manuf.* **2004**, *35*, 371–376. [CrossRef]
42. Baas, L.W.; Boons, F.A. An industrial ecology project in practice: Exploring the boundaries of decision-making levels in regional industrial systems. *J. Clean. Prod.* **2004**, *12*, 1073–1085. [CrossRef]
43. Pietrini, M.; Roes, L.; Patel, M.K.; Chiellini, E. Comparative life cycle studies on poly (3-hydroxybutyrate)-based composites as potential replacement for conventional petrochemical plastics. *Biomacromolecules* **2007**, *8*, 2210–2218. [CrossRef]
44. Vidal, R.; Martínez, P.; Garraín, D. Life cycle assessment of composite materials made of recycled thermoplastics combined with rice husks and cotton linters. *Int. J. Life Cycle Assess.* **2009**, *14*, 73–82. [CrossRef]
45. Bolin, C.A.; Smith, S. Life cycle assessment of ACQ-treated lumber with comparison to wood plastic composite decking. *J. Clean. Prod.* **2011**, *19*, 620–629. [CrossRef]

46. Curran, M.A. Life-Cycle Assessment. In *Encyclopedia of Ecology*; 2nd ed.; Elsevier: Amsterdam, The Netherlands, 2016; Volume 4. [CrossRef]
47. Norgate, T.; Rajakumar, V.; Trang, S. Titanium and Other Light Metals: Technology Pathways to Sustainable Development. In Proceedings of the Green Processing 2004. 2nd International Conference on the Sustainable Processing of Minerals, Fremantle, WA, USA, 10–12 May 2004.