

Environmental Strategies for Sustainable Manufacturing Process of Composites

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Abstract. This research is focused on the strategic road mapping of composite manufacturing process and aims to understand the sustainability and related costs of composite part manufacturing. A manufacturing route of a serial automotive component is mapped and modelled using the following steps: (1) a holistic, cradle to grave product model for both manufacturing and assembly operations, (2) development of life-cycle model and analytical tools, and (3) direct data collection and measure of environmental impacts of manufacturing. Besides the theoretical outcomes recommendations are given considering further recycling and recovery of materials so as to provide further direction for sustainability research in carbon and glass fibre composites.

1. Introduction

The manufacturing and assembly companies use a number of advanced technologies to fabricate parts and finished products from a range of materials such as metals, polymers and carbon or glass reinforced composites [1]. Environmental impact of such materials on landfill is significant and requires investigation and analytical modelling of product life cycle [2,3]. Therefore global engineering companies require further research and support with sustainable development, which includes the four domains: manufacturing, ecology, economics, politics and culture.

Metals, CF-reinforced plastics and ceramics used in automotive for example are energy intensive materials and ideal possible candidates for recycling [4]. However, these materials can be difficult to recycle and re-use in manufacturing for one or more of the following reasons: (1) cross-linking effects in thermosetting polymers prevent re-melting or remoulding; (2) mix of materials in composites are routinely combining many types such as glass and aramid fibres, core materials, paints and so producing multiphase waste; (3) costs and time of materials separation and its recycling are significant, not economic efficient [5-7].

Fundamental research with LCA modelling and manufacturing capabilities has continued to achieve better sustainability with composite materials and related carbon, plastics and metals. A set of new technologies such as chemical recycling, microwave heating, mechanical recovery, and fluidised bed, and pyrolysis [6-10] are being developed; however, a key question whether LCA modelling can capture and address the benefits of new technologies applications in manufacturing, what costs and time involved to replace an old process or supply chain [11-13]. Research at PUEB [14] suggested that using pyrolysis to recover carbon or glass materials from polymer waste will consume only 5-10 % of the energy required to produce a real carbon or glass fibre. For economic gains a cumulative impact from recycling should be less than a combined impact from alternative waste treatment and new material production [15].



For recycled materials their benefits are usually compared with similar properties of engineered materials [16]. Further research using life cycle assessment (LCA) method is required to understand the benefits and limitations of new technologies such as lithography, deposition techniques [17-19]. Changes of properties in recycled materials, coupled with the potential inconsistency of supply and demand, prevent many Polish manufacturing companies from use of recycling technologies. Although the markets for recycled materials grow, a recent technology has identified the needs to speed-up applications for recycled glass fibres (GF), carbon fibres (CF) and also aluminium. Composites and steel products are usually compared in automotive applications but aluminium parts may win over composites in terms of emission benefits. Recycling via pyrolysis notably recovered 98% of carbon materials. Incineration with energy recovery and recycling (fluidised bed and mechanical) are applied for plastics and polymers as well as carbon waste [20].

In this research we aim to develop and demonstrate a holistic LCA modelling approach using the recent advancements in recycling and waste technologies of carbon and glass fibres and polymer materials for potential application in Polish manufacturing industry. This will also include the development of “Eco-design” tools aimed to enhance the modelling capabilities of Polish companies – both small and large manufacturing working in European or global supply chains and aimed to improve their sustainability, efficiency and productivity of operations. A demonstration and validation of research results are planned with industrial partners and academic collaborators as appropriate. In the present work, the LCA methodology is applied to assess the environmental benefits of recycling against other forms of treatment for materials waste, and to evaluate how potential benefits can increase material reuse.

2. Methodology

LCA is an internationally standardized methodological framework [21-23], a part of the ISO 14000 environmental management series, for estimating and assessing the environmental impacts associated with manufactured products over complete life cycles. A product life cycle typically consists of four individual phases: (i) raw materials, (ii) production, (iii) use, and (iv) an end of life. Any actions employed at each life cycle phase consume resources and release emissions that are quantified to determine a total impact of the complete product system as well as relative contribution of each phase [24,25]. The process of LCA involves a 4 step framework as follows:

1. Goal and scope definition: In this stage the aims of study are defined (i.e. to compare the LCA impacts of CFRP door panel Vs steel Vs aluminium).

2. Inventory analysis: In the second stage data is collected. Data is collected on the amount of materials and energy that is consumed to make each product. This data is entered into LCA software (such as software from Carbon Footprint), which becomes an LCA model. The model is built in accordance with standards on LCA, ISO 14040 and ISO 14044.

3. Impact assessment: With LCA software results can be processed and visualised.

4. Interpretation: Results are interpreted to draw conclusions (i.e. product with lowest impact)

Comparison of recycling of a carbon or glass fibres and epoxy composite part via pyrolysis against modern incineration with energy recovery, and disposal via landfilling as potential waste treatments for CFRP waste will be performed. The functional unit for the study is a standard automotive part manufactured at the selected Polish enterprises, related waste and recycling levels.

Life cycle models are compiled within open access software openLCA and commercially available LCA software such as SimaPro and Umberto [26] and the Impact 2002+ impact assessment method [27] is applied to estimate the environmental impacts. The software allows easy input of personalised data and access to the Eco Invent database. After discussing the approach it was decided that the functional unit would be on a “per kg of finished part” basis.

3. Results

Initially, a Process Flow Chart for automotive composite part (a body structure) as seen on Figure 1 is created for both additive manufacturing and traditional composite process technology to map the

manufacturing route and further analyse the potential improvements in product life cycle and costs. The process mapping has also allowed the research project to put a boundary on what should and shouldn't be included in the assessment after discussions with the industrial partners. In further road-mapping processes that have less than a 1% influence on the final output have been left out of LCA modelling. Best practices are developed for LCA, including PAS2050.

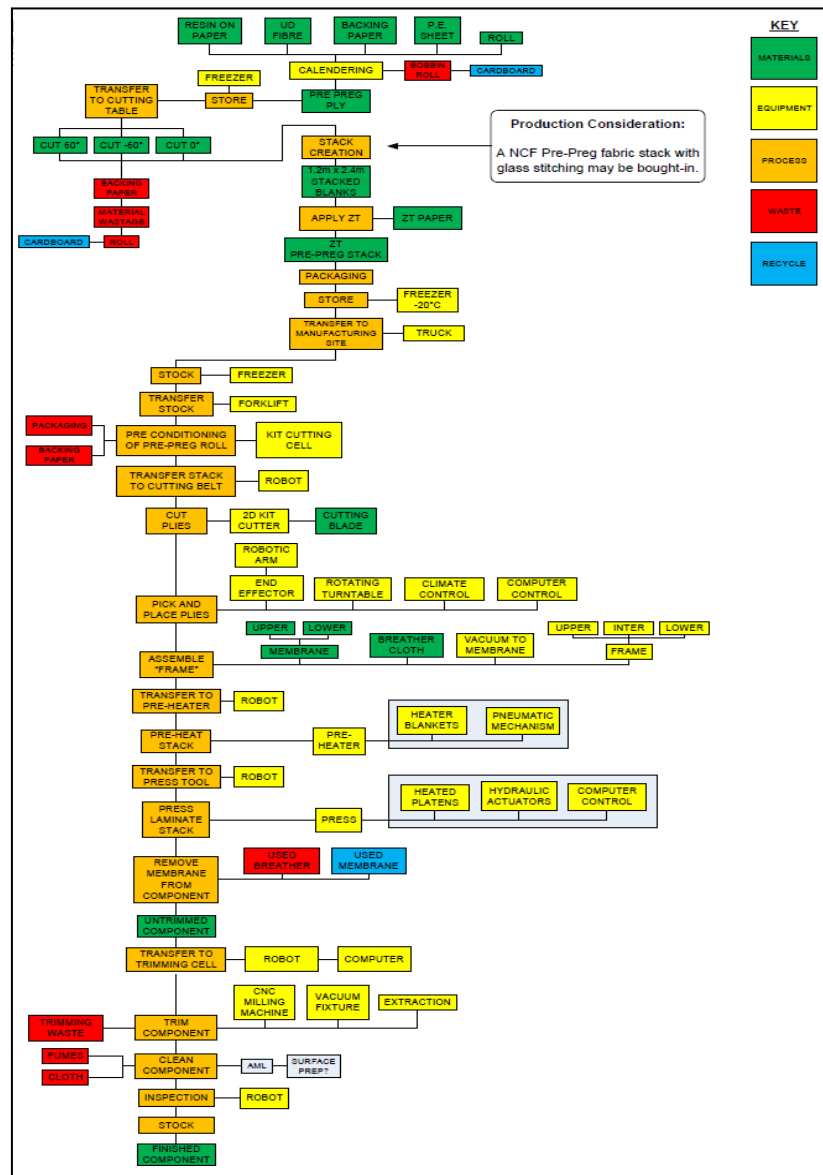


Figure 1. Manufacturing process road mapping for LCA.

Life cycle assessment (LCA) of pre-impregnated (prepreg) composite materials and ones manufacturing using additive manufacturing is presented. To understand the environmental impacts of manufacturing and recycling with carbon and glass fibres as opposite to aluminum a comparative study is done. The LCA is conducted on the current benchmark prepreg to obtain lifecycle results which will be shown in open reports. The benchmark materials are made from woven fabric carbon and thermosetting resins commercially supplied to manufacturing by Toray or similar suppliers. Studies also covered a uni-directional (UD) prepreg to understand the lifecycle properties which could be compared to the woven fabric benchmark. Both prepreps have the same carbon fibre and resin

quantity measured in grams per square metre (GSM). Both of these prepregs are being studied to understand if they can be used on a future body design for body parts of automotive components.

Several steps of LCA have been clarified; the energy consumption of the prepreg production, the type of raw materials, where the raw materials are located, how to transport them, and the waste generated during the production. The entire life cycle assessment required data collection to be done using either measurement or modeling/calculation approach as shown in Fig. 2. This provided data for waste generation and energy consumption during prepreg production.

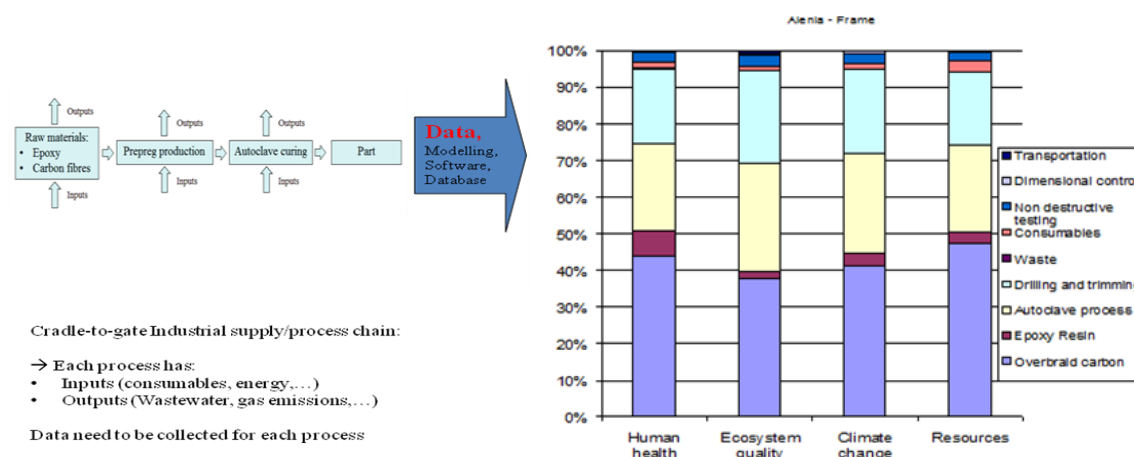


Figure 2. Life cycle assessment and data collection approaches used.

There are two scenarios assumed for carbon fibre composite recycling and re-use. The first approach corresponds to the production and use of carbon fibre-reinforced composites, which is either disposed, through land filling, or incineration, or recycled. Impacts related to each scenario are quantified and compared to determine the most appropriate.

For each waste treatment scenario, the starting point is 1kg of materials waste. The sub-processes included for modelling each making and waste technology route is shown in Figures 1, for land filling, incineration, and recycling respectively. Life cycle inventory (LCI) data will be obtained from Ecoinvent 3.1 LCI database [28] with over 10,000 processes. In each case, waste is first transported with a truck, and then reduced in size by an industrial shredder consuming 0.0025 MJ/kg of electrical energy [29,30]. Transport distances are to be assumed. Electrical energy is produced with the European wide average power mix (nuclear 29%, fossil 52%, Hydro 12%, other renewable 6%) [31-33]. Subsequently this is used in mapping the entire manufacturing and recycling processes and quantify contributions of each sub-process using graphical tools (Fig. 3-4).

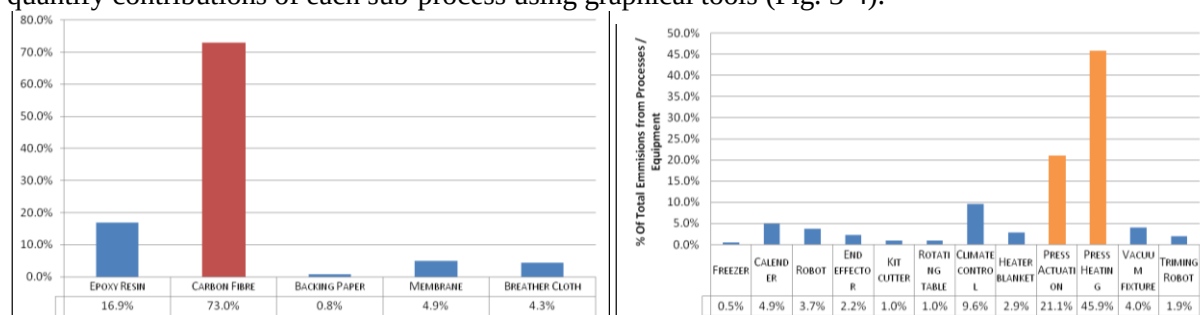


Figure 3. Emissions per raw material (left) and per process operation (right).

The embedded energy in carbon fibre is the biggest contributor to the total emissions (Fig. 3). Depending on the quantity of carbon manufactured, the kgCO₂e/kg will decrease as the quantity increases. According to Harper Beacon, this figure can be as high as 24 for runs as low as 500 MTPY to 16 for runs as high as 2250 MTPY. It is clear that if a reduction in the kgCO₂e/kg is sought after, then focussing on the CF manufacturing is a good place to start.

The biggest contributor to the total emissions by process / equipment (Fig. 3 right) comes from the press platen oil heaters. This is based on 2 heaters each using 48 kW for 5 minutes. This may not be truly representative and physical measurements would be recommended as the heaters may use significantly less power once the platens and tool are up to temperature. During the production implementation newer designs of heated platens are available and significantly decrease the energy consumption. The majority of total emissions generated by using the manufacturing technique come from the raw materials. The total emissions from the traditional composite manufacturing technique are 25.8 kgCO₂/kg. 79% of emissions come directly from the raw materials, 20% from the actual manufacturing of the components and only 1% from transportation (Fig. 4).

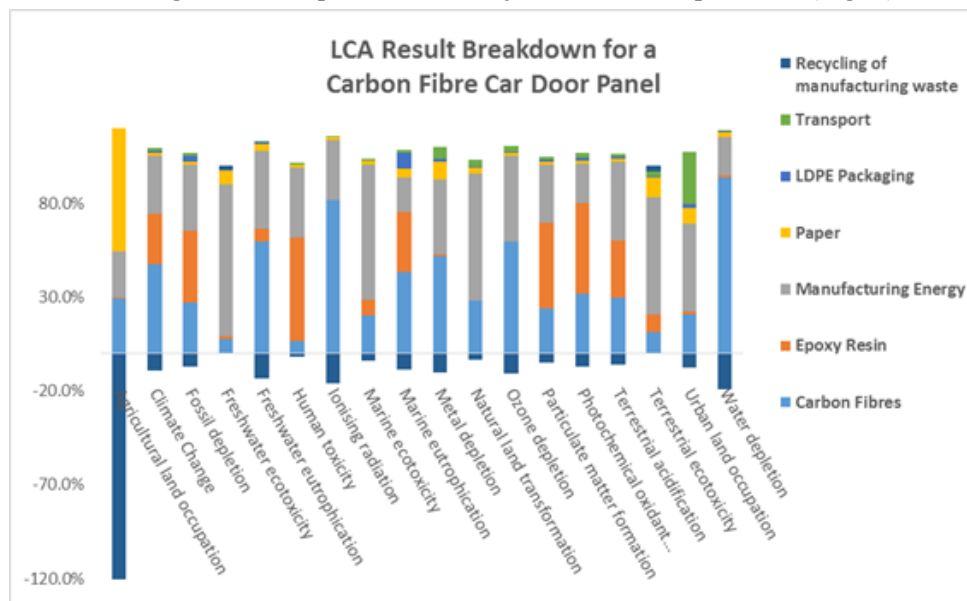


Figure 4. Contributions to each environmental impact category for manufacturing of composite part.

To compare the carbon fibre component to an equivalent stamped aluminium component would require going through the same process as was demonstrated. From the analysis, the embedded energy in the carbon fibre and resin are the biggest contributors to the overall kgCO₂. This is 18.6 kgCO₂/kg. To compare this to an equivalent aluminium component, the embedded energy would be 3.3 kgCO₂/kg. From the analysis, the embedded energy in the carbon fibre and resin is used as comparison criteria contributors to the overall kgCO₂.

For the recycling strategies of composites there are several scenarios assumed. In first scenario, disposal of waste occurs in a sanitary landfill to be constructed on site. Landfill gas is extracted and used for heating in this case without energy recovery. Other emissions could be from construction and related transport equipment at this site. LCI data for landfill of mixed plastics is used as compared to specific materials data from manufacturing. Landfill construction, wastewater treatment and emissions from operation will be considered in the LCA approach.

In a second scenario, a thermal waste treatment process such as incineration is assumed to convert waste material into flue gas, ash, heat, enabling embodied energy to be reduced.

In a third scenario, fibre recovery is achieved via pyrolysis technology to be added to LCA modelling. LCI for carbon or glass fibre recycling has not been found [34]; however, process specific assumption can be made based upon literature and the technical specifications of a commercial pyrolysis process [35-37]. Energy requirements for the recovery of 1 kg of CF are reported to be approximately 10% of that required to produce carbon fibres originally. Emissions from matrix combustion are assumed to be the same as from the incineration of plastics waste [38, 39]. The study has not expanded to the use phase of a vehicle made from recycled materials either carbon or glass fibre composites but other studies may be needed [40-42].

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