Life Cycle Assessment of Composite Materials: a literature review

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Abstract: In this literature review seven papers related to the environmental impact of composite materials are analysed. In the first part the advantages of composite materials with respect to metal alloys are pointed out. Each reviewed paper is splitted into the steps of the LCA: Goal and Scope definition, in which arises that 43% of the papers analyse the impact in the automotive field while the 57% in the aerospace field; Life Cycle Inventory, in which arises that the 71% of the papers gathered data from Ecoinvent and literature; Life Cycle Impact Assessment and results interpretation, in which arises that in 71% of papers Midpoint Impact Categories are used as environmental impact assessment method. It can be observed that no one of the papers considers the high strength properties of composites, this could lead to an overestimation of their environmental impact.

1. Introduction

Composite materials are widely used in aerospace field due to their good properties in terms of weight and strength, in fact, if compared to a typical aeronautical aluminium alloy, composite materials are roughly 30% lighter and almost 250% more strength. From this comparison one can understand why composites are so diffused in aerospace field. Since the usage of composites allows aircraft to be lighter less fuel is needed to flight, so it would be interesting to understand the impact of these materials on the environment. This literature review is intended to provide an overview on the impact assessment of composites by means of Life Cycle Assessment. Seven papers have been analysed, some of them are related to the aerospace field and the others to automotive field.

This literature review is structured by dividing the LCA in its steps: Goal and Scope definition, Life Cycle Inventory Analysis and Life Cycle Impact Assessment. The discussion of the results will be also evaluated. For each step of the LCA the aforementioned steps are put in evidence for each reviewed paper in order to understand how the environmental impact of the composite materials has been evaluated in the world up to now.

2. Life Cycle Assessment overview

In the subsequent paragraphs an overview of the Life Cycle Assessment related to composite materials will be carried out putting in evidence what has been done on LCA for each of its steps.

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2.1. Goal and Scope definition

This paragraph is intended to provide and overview of the goal and scope definition considered in the analysed scientific works; boundaries and functional units are also considered. Most of the scientific papers on composite materials are related to their usage in the automotive or aerospace field.

(Song et al., 2009) take into consideration the environmental impact of composites in the automotive field. The authors analysed two scenarios in which the substitution of the rear part of a truck and a bus are compared. Both the rear parts of the vehicles are made of steel; first a substitution with a component made of Glass Fiber Reinforced Polymer (GFRP) is considered, then with a component made of aluminium alloy. They considered as boundaries from cradle to grave and the weight saving allows by the composite is taken into account. The functional unit considered is the material needed to provide the same stiffness of the replaced component.

The objective of (Al-Lami et al., 2018) is to study the Eco-Efficiency, taking into consideration the production phase for both economical and ecological point of view of the production of Carbon Fiber Reinforced Polymers (CFRP) ribs for aeronautical application. The chosen functional unit is the rib itself and the boundaries considered are from gate to gate.

(Khalil, 2017) wants to assess the impact of CFRP in aerospace field. This work has many objectives: comparison of the energy intensity and impact categories associated with Polypropylene resin (PP) and Epoxy resin (EP), comparison of impact categories associated with the substitution of the Boeing B737-800 fuselage material's from AlMg3 to CFRP, comparison of energy intensities associated with the production of CFRP containing different percentages of fiber, comparison of energy intensities associated with high-volume production with low-volume production and comparison of energy intensity and impact categories associated with recycled Carbon Fiber (CF) from EoL-CFRP with PP vs EP. The functional unit considered is the production of 1 m^3 of aircraft material, so it can be seen that no consideration about the strength improving of CFRP is considered. The boundaries considered are from cradle to gate and form grave to grave.

(Timmis et al., 2014) want to point out the reduction of impact due to the weight saving provided by CFRP in a portion of the aircraft Boeing 787 fuselage. The boundaries are intended from cradle to grave. As a first stage the authors want to compare the same fuselage part made of CFRP and made of aluminum alloy. The functional unit considered is the tonne-kilometre. The goal is to compare two scenarios: CFRP vs Al1, which means fuselage made of aluminum alloy with buy to fly ratio = 1 and CFRP vs Al2, which means fuselage made of aluminum alloy with buy to fly ratio = 8, the latter is a more realistic scenario.

(Vita et al., 2019) want to compare the environmental impact of two different CFRP production techniques: autoclave curing and pressure bag molding (PBM) for the production of the rear diffuser of a luxury car. The functional unit considered is the production of the component itself. The boundaries are considered from cradle to grave. Many scenarios are taken into account considering different materials for the mold, production method, production volume and disposal method for the ancillary products: landfill and incineration. (Gomez-Campos et al., 2020) considered a sandwich panel for aeronautical application made of flax natural fiber with epoxy resin. The main goal is to compare the environmental performance of the bio composite panel with the performance of a conventional panel with skins made of GFRP and a honeycomb core in aramid fibre paper. The boundaries considered are from cradle to grave. The functional unit is defined as the use of 1 m^3 of sandwich panel as interior fitting elements of the airplane A320 NEO.

In (Roy et al., 2020) two automotive components are compared in terms of environmental impact, one made of conventional composite material (with polypropylene (PP) resin), the other made of bio composite material with reinforcement fibers made of miscanthus with PP resin. Two boundaries are taken into consideration: from cradle to gate and from cradle to grave. The functional unit considered is the component itself.

By looking at the previous scientific works it can be noticed that three of seven reviewed papers (~43%) analyze the impact of composite materials in the automotive field, while, the remaining four papers (~57%) analyze the impact in the aerospace field.

Another consideration can be made about the boundaries considered, in fact, four of the reviewed papers (~57%) take as boundaries from cradle to grave, one paper (~14 %) takes as boundaries from gate to gate, one paper (~14%) takes as boundaries both cradle to gate and grave to grave and one paper (~14%) takes both boundaries cradle to gate and cradle to grave.

For what concerns the functional units taken into consideration them are diversified, more in detail: three papers (~43%) take as functional unit the production of the component itself, two papers (~29%) take as a functional units the production of 1 m^3 of material, one paper (~14%) uses the material needed to provide the same stiffness of the replaced component and one (~14%) uses the tonne-kilometre as a functional unit.

2.2. Life Cycle Inventory

In (Song et al., 2009) the energy intensities for the production of the materials such as polymers, fibers and metals are taken from the literature, one of the major data source is (Ashby*, 1992).* For what concerns the energy intensities of the manufacturing methods the majority of the data are taken from the literature, only one data is estimated by the authors: the autoclave molding energy intensity.

(Al-Lami et al., 2018) considered the production phase of composite ribs, the technological process is splitted in unit processes and for each one the inputs and outputs are identified. The authors considered also the ancillary products such as the vacuum bag, acetone and tacky-tape. The process parameters per kg of rib, such as the electricity, autoclave operation, CNC cutter operation, are estimated by German Aerospace Center (DLR) in its laboratories, where the ribs are manufactured.

In (Khalil, 2017), the author, due to the lack of foreground data in the Ecoinvent v2.2 LCI database, gathered informations from the literature such as (Delmonte, 1981), (Agarwal and Broutman, 1990) and (Morgan, 2005). The database Ecoinvent v2.2 LCI was used as secondary data source. The unit processes to produce a CFRP component are pointed out, for each of them all the intermediate flows and elementary flows are described.

In (Timmis et al., 2014) the majority of the data are gathered from Ecoinvent database. Moreover, since the analysed aircraft (Boeing 787) is well known to be the aircraft with the major composite material content, there are many data of public availability. The remaining data, such as the geometry of the structure are estimated by assuming the fuselage to be circular and its thickness is derived by reversing the equation that relate volume to mass.

In (Vita et al., 2019) the data for the production of the fibers are taken from the literature while energy for cutting the plies is measured directly from the cutting machine, being the latter in the laboratory where this research has been carried out, for secondary data Ecoinvent database has been used.

In (Gomez-Campos et al., 2020) some information for the Life Cycle Inventory, such as electricity production, raw materials and transport processes are gathered from the database Ecoinvent v3.4, other informations, such as the electricity needed for the production of the panel, are acquired from the panel producer company. For both the panel types analyzed in this paper, the unit processes are identified and the intermediate flows are pointed out.

In (Roy et al., 2020) both the estimated and literature data are used to evaluate the life cycle environmental impacts of the automotive components. Miscanthus grass cultivation data are collected from the literature. The automotive components manufacturing data are collected from the pilot-scale experiment (Bioproducts Discovery and Development Centre, University of Guelph). The fuel consumption in the use phase is estimated based on a published methodology (Kim and Wallington, 2013). Note that environmental impact of colorant and PP are taken from the Ecoinvent database, while, the impact of the miscanthus is derived by modelling all the unit processes by using a software.

By looking at the various data sources showed in the analyzed papers five categories are identified:

- Literature
- Estimated by the authors
- Measured in situ (it is intended the context in which the research take place, for instance the laboratory)
- Ecoinvent database
- Gathered from the company (it is intended the company/companies involved in the research)

It is interesting to note that the literature source appears in five of the seven analysed papers (~71%), the estimation by the authors appears in three papers (~43%), the in situ measurement appears in three papers (~43%), the Ecoinvent database appears in five papers (~71%) and the gathering from the company appears in one paper (~14%).

In the Table 1 the percentage of flows per type of data sources is shown.

Table 1: percentage of flows covered by the various data sources

Literature	Estimated by the authors	Measured in situ	Ecoinvent	Gathered from the company
37%	9%	21%	26%	7%

2.3. Life Cycle Impact Assessment and results interpretation

(Song et al., 2009) used an hybrid approach: the embodied energy for the two case studies (truck and bus) is calculated by using the data coming from the input-output matrices. The environmental indicator is the energy intensity. Results shows that composite leads to high energy saving during the use phase, in fact, it leads to positive benefits on the bus case which has a long distance travelled during its life. Since in the truck case the distance travelled is lower than the bus, aluminium alloy leads to higher benefits due to its easier disposal.

(Al-Lami et al., 2018) used the decision support tool Eco-efficiency Assessment Model (EEAM) to evaluate both the environmental impact and the Life Cycle Costing Analysis. The carbon footprint as kg of CO_2 equivalent is considered. More in detail for each of the flows represented in the inventory it is shown that the most impacting flows are the energy, which contributes for a 23%, and the fiber, which contributes for a 68%. Another point of view which allows to identify the most impacting phases in the production procedure is provided by the impact for each unit process, in particular it is shown that the impact due to the fiber is located in the cutting phase (the first unit process) because of the fiber waste, while, the impact due to the energy is located in the curing phase, due to the electricity need for the autoclave.

In (Khalil, 2017) the midpoint impact categories, such as ozone depletion potential, ecotoxicity, acidification potential, global warming potential and kg of SO_2 equivalent are considered. The software used in this work is OpenLCA. The author found that the aircraft fuselage made of AlMg3 has a carbon footprint 1.7 greater than the one made of CFRP. For what concerns the sensitivity analysis on the fiber fraction of the CFRP it can be seen that the eutrophication potential is the most sensitive to the variation of the fiber content percentage, on the other hand, the ozone depletion is the less sensitive. In this paper it is also analysed the environmental impact of the high-volume production vs the low-volume production and it was found that the ozone depletion is the mid point impact category most affected by this factor, while, the less affected is the eutrophication potential. It is interesting to note that the ozone depletion is the most sensitive because the prepreg plies must be refrigerated; this refrigeration is needed especially in low volume production. For what concerns the disposal phase the composite with PP and EP are compared and it can be noticed that in almost all the midpoint impact categories the impact of the composite with PP is lower than the one with EP.

(Timmis et al., 2014) considered the single score environmental impact to compare the scenarios and for each scenario the CO_2 and NO_x emissions are pointed out. The software to carry out the LCA is SimaPro 7.2. This study shows that considering only manufacturing and disposal phase the CFRP configuration has an higher impact with respect to the aluminium alloy configuration, on the contrary, if the use phase is considered in the LCA it can be seen that the CFRP configuration is the less impacting. This is due to the weight saving obtained with the usage of composites. The most used resources are the fossil fuels, that, when only manufacturing and disposal are considered are related to the production of the carbon fiber, while, if the full LCA is considered, it contributes much more in the use phase.

In (Vita et al., 2019) the impact evaluation results are obtained by using the software SimaPro 8.0.5.13 and in particular the impact indicators are expresses with two methods: Climate change midpoint category (measured in kg of CO_2 equivalent) and ReCiPe Endpoint (H)--Europe H/H single score (measured in EcoPt). By comparing two production methods, autoclave and Pressure Bag Molding, it can be seen that the autoclave process has a lower environmental impact with respect to PBM, this is due to the usage of consumables (such as inflatable and molds) and mold cooling, referring to PBM. The less impacting scenario is the one with aluminum mold cured in autoclave. It can also be observed that the most impacting factor, among all the scenarios, is the production of the prepreg. The environmental impact, for all the scenarios, increases linearly with the production volume. It is also pointed out that the EoL impact is small in all the scenarios if compared to the other phases.

(Gomez-Campos et al., 2020) evaluated the impact with the method ILCD 2011 Midpoint+ and the software SimaPro 8.5.2. Results shows that the bio composite panel has a greater impact with respect to the conventional one due its higher weight, for all the impact categories, fuel consumption is strongly dominating over 90%. If only cradle to gate boundaries are considered the bio composite panel has a lower environmental impact and it can be seen that the major contributions are in the production of the flax textile, due to the agriculture activity.

In (Roy et al., 2020) many impact categories are taken into consideration such as ozone depletion, global warming, smog, acidification and others. The software used to evaluate the environmental impact assessment is SimaPro 8.0.4.26. Results shows that comparing the two materials only in the manufacturing phase the lower environmental impact in terms of GWP is achieved by the conventional composite, this is due to the material production. Moreover, among the material production for the bio composite, the production of the PP resin is responsible for 87% of GWP. The bio composite solution has the lower environmental impacts mainly because of fuel saving during its use.

By looking at the analysed papers it can be seen that for what concerns the environmental impact comparison methodologies only one of the reviewed papers (~14%) uses the energy intensity, five papers (~71%), uses the Midpoint Impact Categories and one (~14%) uses the Single Score Environmental Impact.

Taking into consideration the software used to carry out the LCIA it can be seen that in four papers (~57%) the software SimaPro is utilized, in one paper (~14%) the used software is OpenLCA, in one paper (~14%) the EEAM decision support model is used and in one paper (~14%) it was not specified.

In the Table 2 the main aspects of the LCA in the analyzed papers are summarized.

Table 2: Main aspects of LCA for each analyzed paper

Authors	Application field	Boundaries	Functional unit	Data source	Impact indicator
Al-Lami et al.	aerospace	gate to gate	component itself	measured in situ	midpoint
Gomez-Campos et al.	aerospace	cradle to grave	1 m^3 of material	Ecoinvent, company	midpoint
Khalil	aerospace	cradle to gate, grave to grave	1 m^3 of material	literature	midpoint
Roy et al.	automotive	cradle to gate, cradle to grave	component itself	estimated, literature	midpoint
Song et al.	automotive	cradle to grave	material to give a certain stiffness	literature	embodied energy
Timmis et al.	aerospace	cradle to grave	tonne-kilometre	Ecoinvent	single score env. indic.
Vita et al.	automotive	cradle to grave	component itself	literature, measured in situ	midpoint

3. Conclusions

By looking at the papers reviewed in this work the following considerations can be pointed out:

- Composite material structures shows to have a lower environmental impact with respect to a metallic structure only if the usage phase of the product is taken into consideration;
- Typically the production and the disposal of composite materials are more impacting with respect to metal alloys;
- The usage of polypropylene resin for composites may lead to a less impacting disposal phase but further studies on the material's mechanical properties must be carried out;
- In all the analyzed papers only density comparison between metal alloys and composites are done but no one considers the increasing of strength coming from the usage of composite

materials, which may leads to a further weight reduction, and thus, it may leads to a lower environmental impact;

- Although bio composite materials are less impacting in the production and disposal phases, their usage in aerospace field is still limited due to the weight increasing with respect to standard composites and further design enhancement must be performed.

4. References

Agarwal, BD, Broutman, LJ, 1990. Analysis and Performance of Fiber Composites, 2nd ed. John Wiley & Sons Inc.

Al-Lami, A, Hilmer, P, Sinapius, M, 2018. Eco-efficiency assessment of manufacturing carbon fiber reinforced polymers (CFRP) in aerospace industry. Aerospace Science and Technology. 79 (2018), 669-678.

Ashby, MF, 1992. Materials selection in mechanical design. Oxford: Pergamon Press.

Delmonte, J, 1981. Technology of Carbon Fiber Composites. Van Nostrand Reinhold Publisher.

Gomez-Campos, A, Vialle, C, Rouilly, A, Hamelin, L, Rogeon, A, Hardy, D, Sablayrolles, C, 2020. Natural Fibre Polymer Composites - A game changer for the aviation sector?. Journal of Cleaner Production. 286 (2021) 124986.

Khalil, YF, 2017. Eco-efficient lightweight carbon-fiber reinforced polymer for environmentally greener commercial aviation industry. Sustainable Production and Consumption. 12 (2017), 16-26.

Kim, HC, Wallington, TJ, 2013. Life-cycle energy and greenhouse gas emission benefits of lightweighting in automobiles: review and harmonization. Environ. Sci. Technol. 47, 6089-6097.

Morgan, P, 2005. Carbon Fibers and their Composites. Taylor & Francis, CRC Press.

Roy, P, Defersha, F, Rodriguez-Uribe, A, Misra, M, Mohanty, AK, 2020. Evaluation of the life cycle of an automotive component produced from biocomposite. Journal of Cleaner Production. 273 (2020) 123051.

Song, YS, Youn, JR, Gutowski, TG, 2009. Life cycle energy analysis of fiber-reinforced composites. Composites: Part A. 40 (2009), 1257-1265.

Timmis, AJ, Hodzic, A, Koh, L, Bonner, M, Soutis, C, Schäfer, CW, Dray, L, 2014. Environmental impact assessment of aviation emission reduction through the implementation of composite materials.

Vita, A, Castorani, V, Germani, M, Marconi, M, 2019. Comparative life cycle assessment and cost analysis of autoclave and pressure bag molding for producing CFRP components. The International Journal of Advanced Manufacturing Technology. 105 (2019), 1967-1982.