Materials Research Proceedings 41 (2024) 2871-2880 https://doi.org/10.21741/9781644903131-314

# Finite element analysis and life cycle assessment for CFRP laminates in marine applications

GENTILI Serena[1,a], GRECO Luciano[1,b], FORCELLESE Archimede[1,c], MIGNANELLI Chiara[1,d*], PAPPADÀ Silvio[2,e], SALOMI Andrea[2,f], VITA Alessio[1,g], ZANZARELLI Giuseppe[2,h]

[1]Università Politecnica delle Marche, Via Brecce Bianche 12, 60123 Ancona, Italy

[2]Cetma Composites, Via Enrico Fermi, 5/b, 72100 Brindisi, Italy

[a]s.gentili@pm.univpm.it, [b]l.greco@pm.univpm.it, [c]a.forcellese@staff.univpm.it, [d]c.mignanelli@pm.univpm.it, [e]silvio.pappada@cetmacomposites.it, [f]andrea.salomi@cetmacomposites.it, [g]alessio.vita@staff.univpm.it, [h]giuseppe.zanzarelli@cetmacomposites.it

**Keywords:** Finite Element Method, Life Cycle Assessment, Composite Material, Nautical Applications

**Abstract**. The present study focuses on structural analysis of a moth structure realized in carbon fiber reinforced polymers (CFRPs) prepreg laminates. A finite element method analysis was performed to investigate the flexural strength of different laminations and to identify the optimal layering. Moreover, a Life Cycle Assessment (LCA) analysis was conducted to evaluate the environmental impacts of the moth structure obtained using innovative processes and to compare them with those resulted by the same structure realized with manual composite processes. The results demonstrated the higher sustainability of the innovative process than the traditional one (335.75 eq. vs 228.22 kg $CO_2$ eq.). This research is part of the project NAUTILUS, in which Università Politecnica delle Marche and Cetma Composites are involved, that aims to develop, test and validate new processes for composite materials in nautical applications, with respect to environmental sustainability.

## Introduction

In the last years, prepreg composite materials have emerged as revolutionary solutions in several sectors, for the production of aerospace, automotive, nautical and other high-performance applications, offering an excellent combination of strength, lightness, structural stability and versatility [1].

Furthermore, prepreg composites lead to several advantages as compared to hand-impregnation composites, such as the precise control of the resin content, uniformity and repeatability, high mechanical performances, reduced curing time, and smooth and glossy surface finish [2–5]. However, since the design of the composite laminated products is complex and time-consuming due to the large number of variables to consider, Finite Element Method (FEM) analysis can represent a suitable tool to optimize the composite layering. In particular, by using this method, simulations can be carried out to evaluate the mechanical performances of the composite structure and to define the best sequence of composite laminates based on the defined loading conditions [6,7]. Furthermore, a critical aspect in manufacturing is related to the environmental sustainability of composite materials. Prepreg composites are characterized by the production of a minimum amount of waste, optimizing the use of materials and thus contributing significantly to the environmental sustainability [8,9]. In the scientific literature, few papers on the design of composite nautical structures are available in scientific literature. Peterson investigated the potential application of additive manufacturing with Fiber Reinforced Plastic to the yacht design

Materials Research Proceedings 41 (2024) 2871-2880 https://doi.org/10.21741/9781644903131-314

and manufacturing industry [10]. Bianchi et al. focused their attention on a simplified model for structural analysis of hydrofoil and moth masts realized with composite laminates [11]. Castegnaro et al. studied the bio-composite structures for the racing sailboats to cope with the environmental issues [12]. However, literature lacks environmental assessments of racing nautical structures and comparisons between the impacts of composite prepreg parts and ones produced via manual composite lamination.

Recently, the Italian Ministry of Economic Development funded a research project in which Università Politecnica delle Marche and Cetma Composites are involved, that concerns the development of innovative composites manufacturing processes for advanced racing nautical structures, characterized by lower environmental impacts than the traditional alternatives. In this context, this paper provides an environmental assessment of the use of carbon fibres (CF) prepreg for the production of a moth, that is a racing nautical structure. In addition, a comparison with an equivalent component produced using dry CF fabric and a manual lamination process was conducted. Given the interest in sailing competition and amateur applications, the moth structure was selected as representative case study to contribute to a sustainable development of high-end nautical component. The study aims to evaluate the difference between the use of dry fibres and resin, and prepregged fibers as composite material used to realize a moth structure. The goal is to identify which is the more sustainable solution. FEM analyses were employed to define the composite layering which guarantee the required mechanical performances and consequently the related weight. The latter represents an important input data for the environmental evaluation. The standardized methodology of Life Cycle Assessment (LCA) was used to identify which is the more sustainable solution.

## Material and methods

### Design phase

The moth structure is a racing sailing sailboat featured by hydrodynamic appendages called hydrofoils, which are submerged laminar surfaces with similar characteristics of aircraft wings. They are designed to generate vertical thrust as the boat speed increases, allowing the lift of the structure above the water level. This led to a minimization of the hydrodynamic resistance of the hull and the achievement of high sailing speeds and greater hydrodynamic efficiencies than traditional sailboats. For this reason, the CFRP results the most suitable material for this structure.

Firstly, the design phase needed the initial CAD model of the structure, which was provided by the Cetma Composites team, which also assessed the loads applied to it as well as the safety factor requirements of the structure. Then, several simulations based on the Finite Element Method (FEM) were carried out by using Siemens NX software.Figure 1 shows the CAD model of the moth structure investigated. An iterative process was performed to analyze the structural strength of the moth as a function of the structure thickness. This analysis allowed to identify the optimal prepreg layering in different areas of the moth, ensuring sufficient strength and stiffness while keeping a low weight of the structure.

### Life Cycle Assessment of the moth structure

The environmental impacts associated with the moth structure were evaluated through the LCA methodology. It is based on the UNI EN ISO 104040 – 14044 standards. The main phases of the LCA procedure are: i) goal and scope definition, ii) Life Cycle Inventory (LCI), iii) Life Cycle Impact Assessment (LCIA) and iv) Interpretation of results.

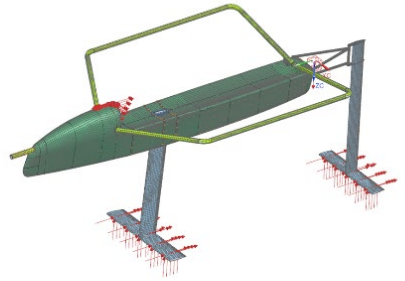

*Figure 1 CAD model of moth structure.*

**Goal and scope definition**

The LCA analysis aims at quantifying and comparing the environmental impacts associated with two different typologies of the moth structure production to identify which is the most sustainable solution. The functional unit (FU) is defined as “the production of a composite material moth structure of 6.71 kg”. The Life Cycle Assessment is based on a “from cradle to grave” approach, as it includes life cycle phases from the extraction of the raw materials to the disposal of the final product. More specifically, materials extraction, production of consumables, manufacturing and disposal are included within system boundaries. The service life is not included because the focus of the study is the environmental effects associated to the use of different materials.

Two different scenarios were considered in this analysis, which differ in terms of the typology of raw materials used. The description of the considered scenarios is reported below.

- *Scenario 1*: it includes the production of the moth structure made by CFRP composite manually impregnated. An epoxy resin is considered as the composite matrix. The process used to produce the structure is a manual lamination followed by a curing process at room temperature. The same materials and processes were considered to realize the mold for the moth structure. In addition, a milling process is considered to produce a polyurethane master used to realize the composite mold. Then, a landfill disposal is considered as end-of-life phase.
- *Scenario 2*: it includes the production of the moth structure made by a CFRP prepreg, with an epoxy resin matrix, as for the Scenario 1. A manual lamination followed by an oven curing process is considered to produce the structure. The same CFRP prepreg and the described process were considered to realize the composite mold. Moreover, as for the Scenario 1, the production of a polyurethane master to obtain the composite mold, through a milling process, was included. Then, a landfill disposal is considered as end-of-life phase.

Both scenarios include landfill disposal for the components as, at present, this is still the most common EoL alternative for thermosetting matrix composite materials. Figure 2 shows a schematic representation of the phases included within the system boundaries of the analysed scenarios.

**Life Cycle Inventory**

Different sources were considered for the collection of the Life Cycle Inventory data: primary data were measured directly, while secondary data were retrieved from scientific literature and Ecoinvent 3.1 commercial database [13]. A detailed description of the LCI phase and data retrieval is reported below. At first, inventory data related to the moth structure are listed, then data concerning the production of the moth mold and the master are given. The main inputs to realize the moth structure are the material used: carbon fibres and epoxy resin for both scenarios. Since the Scenario 1 does not consider the use of a prepreg, the quantity of each material used is higher than the one considered in the Scenario 2.

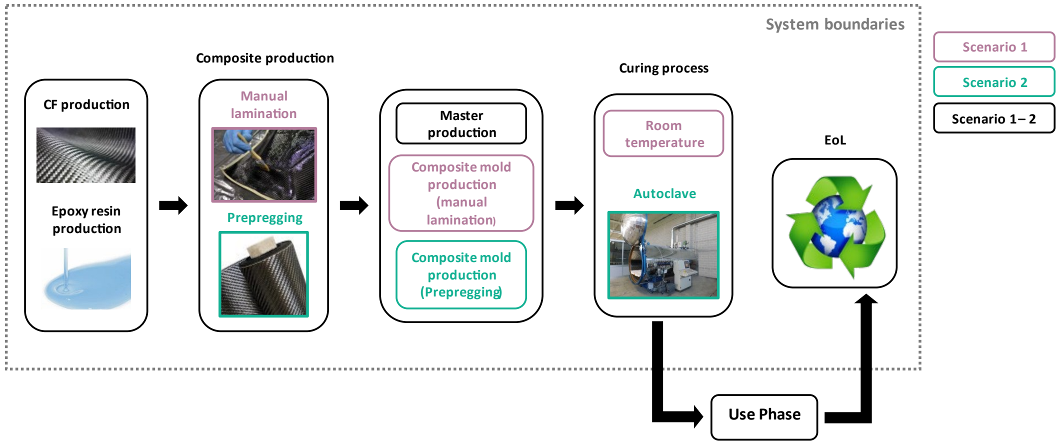


*Figure 2 System boundaries of analysed scenarios.*

In fact, prepreg offers a good control of resin content which cannot be guaranteed by impregnating the fibres in a resin bath. By considering a composite with 60wt% of fibres and 40wt% of matrix, 4.8 kg of epoxy resin and 7.2 kg of carbon fibres are considered in the Scenario 1, while 2.68 kg of epoxy resin and 4.03 kg of carbon fibres are analysed in the Scenario 2. Since the impregnation process included in the Scenario 1 is a manual process, no energy consumption is considered, while in the Scenario 2 an energy consumption of 40 MJ per kg of composite is included for the realization of prepreg [14]. To fabricate the moth structure a manual lamination process is used, so no consumptions are considered. An oven curing process is considered only in the Scenario 2, because the Scenario 1 includes a curing process at room temperature. The consumptions related to this process are the needed energy and the consumable materials as the polyamide (PA66) for the vacuum bag, the polyethylene (PET) for the breather, the polypropylene (PP) for the release film and a synthetic rubber for the sealant tape. Table 1 summarizes the moth inventory data.

*Table 1 LCI input data of moth structure.*

| **Input** | | **Quantity** | | **Unit** |
|---|---|---|---|---|
| | | *Scenario 1* | *Scenario 2* | |
| **Materials** | Epoxy resin | 4.8 | 2.68 | kg |
| | Carbon fibres | 7.2 | 4.03 | kg |
| **Production** | Prepregging | - | 40.0 | MJ/kg |
| **Curing process** | Vacuum bag (PA66) | - | 3.0 | kg |
| | Breather (PET) | - | 1.2 | kg |
| | Realase film (PP) | - | 0.4 | kg |
| | Sealant tape (Synthetic rubber) | - | 0.945 | kg |
| | Energy | - | 6.0 | kWh |

The same materials and processes described above w considered for the realization of the mold used to produce the moth structure. The inventory data related to the mold production are reported in Table 2. To obtain a consistent analysis it is necessary to divide these values by the number of moth structures produced with a mold during its service life, which is about 100 for the Scenario 1 and 200 for the Scenario 2. As previously mentioned, the production of the master to realize the mold of the moth is considered within the system boundaries of the analysis. Table 3 reports the inventory data related to the master production. It includes the material used (polyurethane) and a milling process. As for the mold, to gain consistent results the values reported in Table 3 have to be divided by the number of moth structures produced with a master during its service life, which is about 1000 for Scenario 1 and about 2000 for Scenario 2. All reported data are directly measured except for the energy consumption related to the prepregging process which was retrieved by literature [14]. The quantity of composite material considered in the Scenario 2 is an output of the design phase: the corresponding weight value to the optimal stratification.

*Table 2 LCI input data of mold.*

| **Input** | | **Quantity** | | **Unit** |
|---|---|---|---|---|
| | | *Scenario 1* | *Scenario 2* | |
| **Materials** | Epoxy resin | 19.6 | 15.6 | kg |
| | Carbon fibres | 29.4 | 23.4 | kg |
| **Production** | Prepregging | - | 40.0 | MJ/kg |
| **Curing process** | Vacuum bag | - | 4.2 | kg |
| | Breather | - | 1.8 | kg |
| | Realase film | - | 0.6 | kg |
| | Sealant tape | - | 1.26 | kg |
| | Energy | - | 5.0 | kWh |

*Table 3 LCI input data of the master.*

| **Input** | **Quantity** | | **Unit** |
|---|---|---|---|
| | *Scenario 1* | *Scenario 2* | |
| **Polyurethane** | 501.8 | | kg |
| **Polyurethane removed by milling** | 144.8 | | kg |

## Life Cycle Impact Assessment

The LCIA phase is important to choose the impact categories to allow the achievement of consistent, relevant, and reliable results. In fact, by considering different environmental indicators and analysis methods, a comprehensive view of the environmental effects of the two analysed scenarios can be obtained. This study considered two different impact assessment methodologies: Global Warming Potential (GWP) and ReCiPe. To simplify the translation of inventory data to the chosen impact categories, the LCA SimaPro software was used.

## Results and discussion

The design phase led to the identification of the optimal composite layering of the moth structure which consists in 6 total layers: 4 unidirectional fabrics with CF oriented toward the length of the hull (0°) and 2 plain fabrics with a CF orientation of 45° with respect to the hull length. This layering resulted in a moth structure of about 1 mm thickness and 6.71 kg weight. This value is the input data related to the composite material considered in the Scenario 2. Figure 3 compares the LCA results of all phases included within the system boundaries of two analyzed scenarios, by considering GWP method.

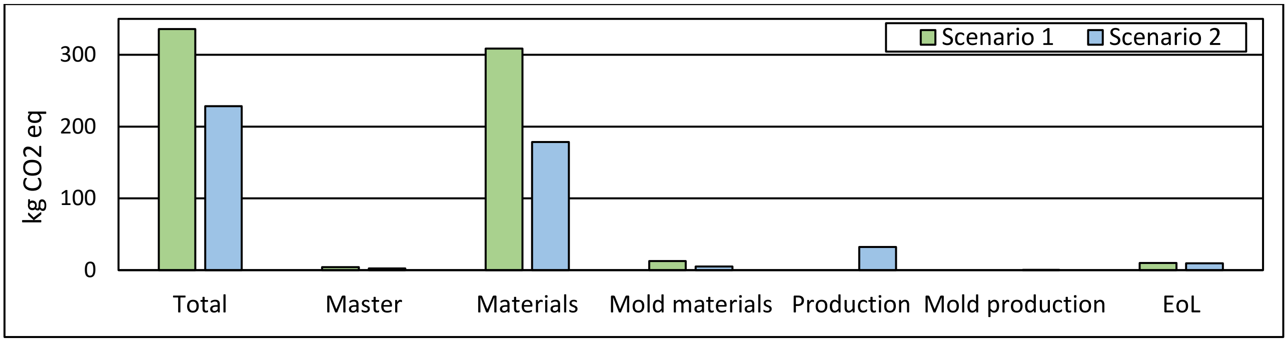


*Figure 3 Comparison between LCA results of Scenario 1 and Scenario 2, GWP method.*

It emerged that the manual impregnation of carbon fibres considered in the Scenario 1 represents a more impactful solution than the use of prepreg of the Scenario 2 (335.75 kg $CO_2$ eq vs 228.22 kg $CO_2$ eq). Such result is consistent to the results obtained by Forcellese et al. in [15]. As highlighted in Figure 3, this result is mainly due to the materials phase, which gives the highest contribution to the total impacts: about 308.66 kg $CO_2$ eq for Scenario 1 and 178.66 kg $CO_2$ eq for Scenario 2. All other phases provide a low environmental load: for the Scenario 2 the second most impactful phase is the production of the prepreg, and this is related to the energy consumption of prepregging and curing processes. Anyway, this value is an order of magnitude lower than the value associated with the materials phase. Moreover, it can be observed that the master production and the mold materials and production give negligible contributions to the total impacts, although the high input values. This result is related to the allocation of the generated impacts to the service life of master and mold respectively. The EoL phase irrelevantly contributes to the total impacts, but it provides negative effects due to the landfill disposal. Different EoL strategies (e.g. mechanical, chemical and thermal recycling) and the recovery of secondary raw materials could enhance the scenarios sustainability and reduce the contribution of raw materials. Hence, a scenarios impact reduction is expected as high efficiency recycling technologies are developed and will become the preferred industrial solution for composite disposal. Since the phase of materials is the most impactful one, it is specifically analysed to identify which material is the most responsible of this high impact value. Figure 4 shows the environmental impacts related to the input materials considered and highlights that the high impact value related to the materials phase is mainly due to the use of carbon fibres. The contribution of epoxy resins and the consumable materials of curing process are negligible. The difference between the environmental impacts provided by carbon fibres in the Scenario 1 and 2 arises from a different input quantity of carbon fibres. The same reason explains the lower environmental impact of epoxy resin in Scenario 2 than in the Scenario 1. As a matter of fact, manual impregnation (Scenario 1) requires a higher quantity of material than the prepreg (Scenario 2) to guarantee the same mechanical properties.

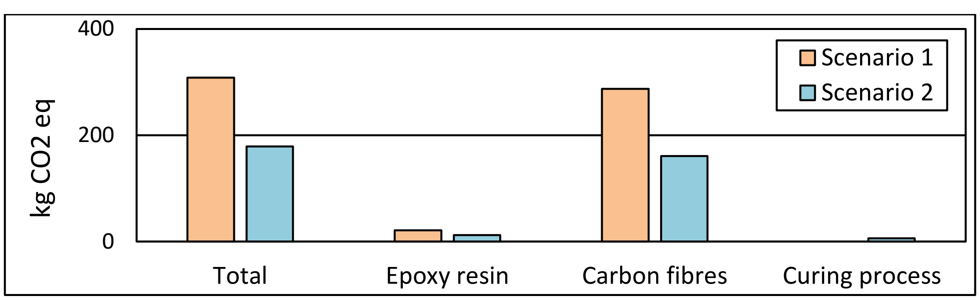


*Figure 4 Comparison between LCA results of materials phase of two scenarios, GWP method.*

Considering the high impacts contribution of raw material, it is clear that an optimal design phase and a minimization of material use are crucial to reduce the overall environmental impacts of the composite structures. The LCA results were also analysed by using ReCiPe method (Figure 5). It can be observed that the results are in line with the ones analysed with GWP method: the most impactful phase is the materials for both Scenario 1 and Scenario 2 in all considered impact categories.

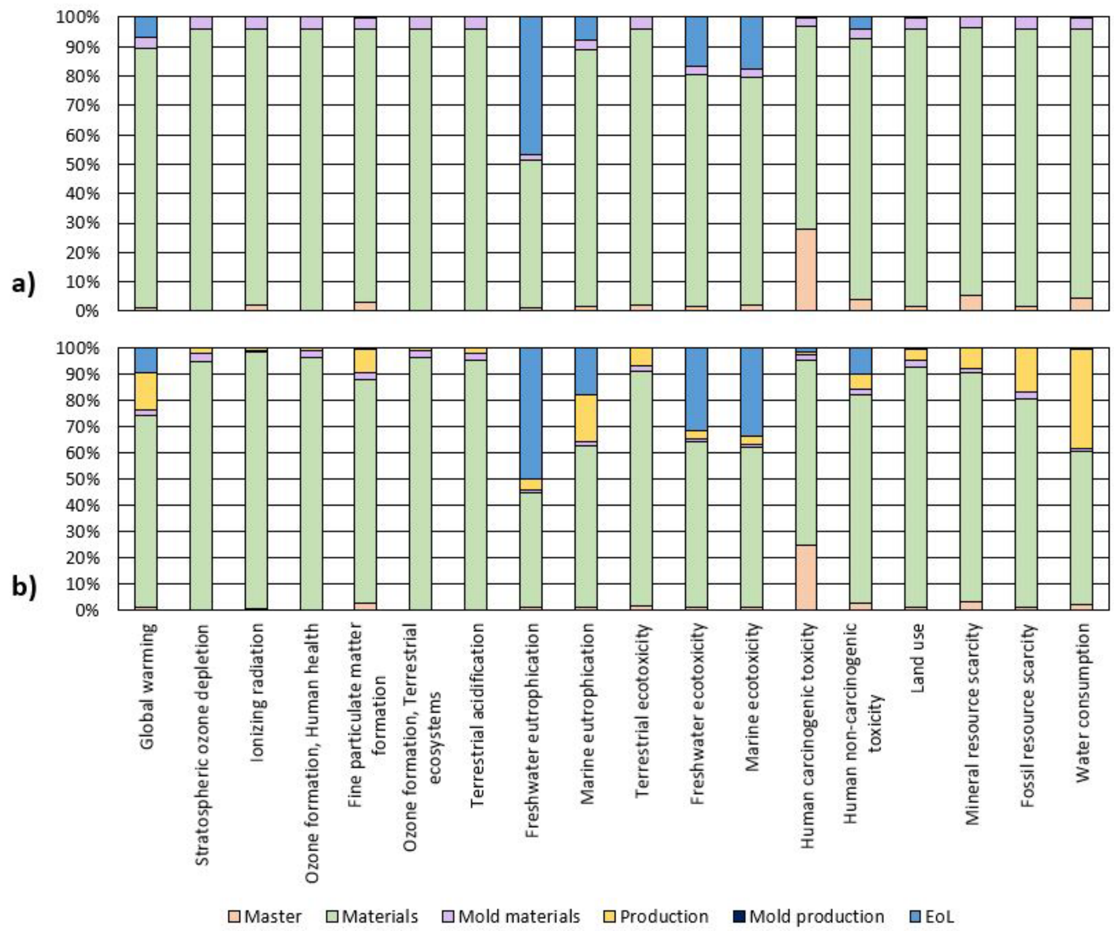


*Figure 5 Comparison between LCA results of Scenario 1 (a) and Scenario 2 (b), ReCiPe method.*

The other phases included in the Scenario 1, so the master, the mold materials and the end-of-life give a negligible contribution in percentage to the total impacts, as shown in Figure 5a. An exception can be made for the "Freshwaster eutrophication" impact category, in which the contribution of the EoL is consistent, comparable to the one related to materials. This result is probably due to the landfill disposal which provides negative effects, especially for this impact category. Moreover, it can be observed a consistent percentage contribution of the master for the "Human carcinogenic toxicity" impact category, and this is related to the use of polyurethane. The same observations can be done for the Scenario 2: Figure 5 highlights that the trend of the results obtained by using ReCiPe methodology is the same for the Scenario 1 and 2. The only difference between the two scenarios is the presence of two additional phases in the Scenario 2: the production of the moth structure and the mold of the moth. Both phases give low percentage contributions to the total environmental impacts. The contributions of the production of the moth for the various impact categories are higher than the ones related to the production of the mold. A consistent percentage value of the production of the moth is observed for "Water consumption" impact category. This result is due to the use of the nylon for the vacuum bag used for the curing process.

Figure 6 shows the comparison between the resulting impacts related to the materials phase in the Scenario 1 (Figure 6a) and the Scenario 2 (Figure 6b). It can be noticed that the main percentage contribution to the total environmental load is provided by the carbon fibres for both scenarios and for all the considered impact categories. The difference between the two scenarios is the presence of the prepregging phase in the Scenario 2, which includes the needed energy consumption to realize the prepreg. However, from Figure 6b emerges that the percentage contribution associated with this phase is much lower than the one related to the carbon fibres for all the impact categories except for the "Ionizing radiation": this result is due to the energy consumption.

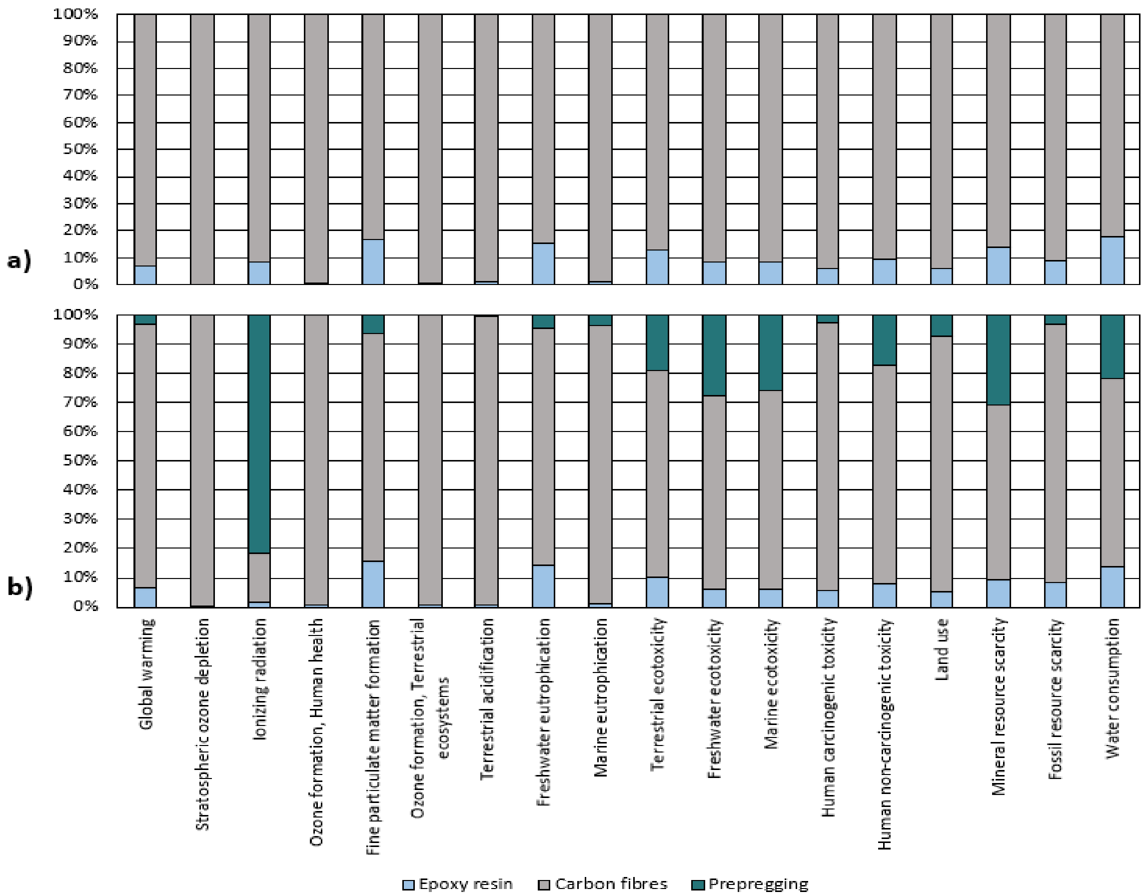


*Figure 6 Comparison between LCA results of materials phase of Scenario 1 (a) and Scenario 2 (b), ReCiPe method.*

A specific analysis of the resulted environmental impacts provided by carbon fibres was conducted to identify what the high value is due to (Figure 7). A single graph is reported because the same trend was observed between two scenarios. It can be noticed that for almost all impact categories, the polyacrylonitrile (PAN) give the highest percentage contribution (nearly 100%) to the total impacts. In addition, it is observed that the percentage contribution of air emissions is higher than the one related to PAN for few impact categories. This means that for few environmental issues the air emissions give more significant negative effects than the PAN production, differently for all the others considered issue. Instead, the nitrogen and heat emissions and the electricity consumption do not significantly contribute to the comprehensive environmental impacts.

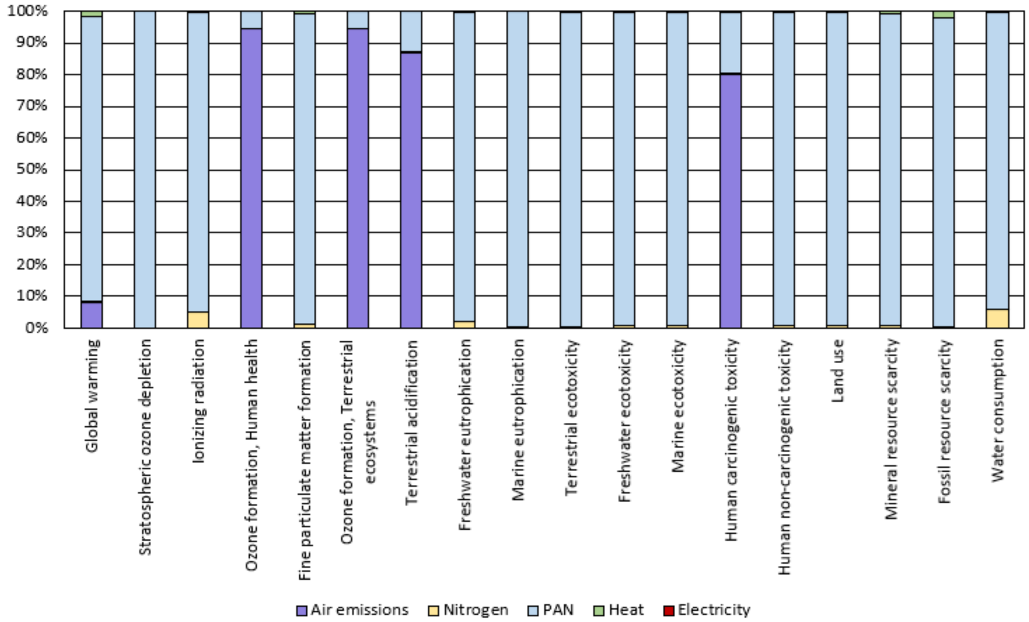


Figure 7 LCA results of carbon fibres, ReCiPe method.

## Conclusions

This study presents the life cycle assessment of a moth structure focusing on the materials and production: two scenarios were investigated. The scenario 1 considers the production of a moth structure starting from a CFRP manually impregnated while the scenario 2 considers the production of a moth structure by using CFRP prepreg. The main results obtained are summarized as follows:

- As a general outcome, the use of prepreg (Scenario 2) represents a more sustainable solution than the use of CFRP manually impregnated (Scenario 1). Specifically, in terms of Global Warming Potential, the Scenario 1 provides 335,75 kg $CO_2$ eq, while the Scenario 2 shows impacts equal to 228,22 kg $CO_2$ eq. This result is mainly due to the lower quantity of carbon fibres considered in the second scenario than in the first one.
- The materials phase is the most impactful: it provides 308,66 kg $CO_2$ eq for Scenario 1 and 178,66 kg $CO_2$ eq for Scenario 2. The carbon fibres give the highest contribution to the total environmental impacts, and this is related to the production of the PAN.
- The results analyzed by GWP and ReCiPe methods have the same trend.
- No advantages are gained from the EoL phase as no composites recovery processes are considered.

Research activities are in progress to increase the sustainability of this structure, by consider bio-composites as raw material and different end-of-life scenarios. Combustion and mechanical recycling processes can be considered in the analysis to evaluate the associated potential reduction in the total environmental impacts. In this way, it will be possible to identify which process represents the more sustainable solution. Moreover, a cost analysis, through the Life Cycle Costing methodology, can be carried out to identify if the use of prepreg represents a more economically sustainable solution too.

## Acknowledgements

This research was supported by the project titled “NAUTILUS: Progetto di Ricerca e Sviluppo di Nuovi Processi ad Alta Efficienza per la Produzione di Strutture ad Elevate Performance per la

Nautica", co-financed by the Italian Ministry of Economic Development as part of the Fund for Sustainable Growth - "Fabbrica intelligente" PON I&C 2014- 2020 (project F/190047/01-03/X44).

## References

[1] M. Holmes, "Carbon composites continue to find new markets," *Reinforced Plastics*, vol. 61, no. 1, pp. 36–40, Jan. 2017. https://doi.org/10.1016/J.REPL.2016.12.060

[2] W. Jarrett, S. P. Jeffs, F. Korkees, and M. Rawson, "The opportunities and challenges of hybrid composite driveshafts and their couplings in the aerospace industry: A review," *Compos Struct*, vol. 320, p. 117203, Sep. 2023. https://doi.org/10.1016/J.COMPSTRUCT.2023.117203

[3] P. Singh *et al.*, "Composite material: A review over current development and automotive application," *Mater Today Proc*, Nov. 2023. https://doi.org/10.1016/J.MATPR.2023.11.012

[4] F. Rubino, A. Nisticò, F. Tucci, and P. Carlone, "Marine Science and Engineering Marine Application of Fiber Reinforced Composites: A Review". https://doi.org/10.3390/jmse8010026

[5] J. A. Satterwhite *et al.*, "Achieving process flexibility in next-generation carbon fiber prepreg material," in *International SAMPE Technical Conference*, 2017, pp. 2433 – 2446. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85044635534&partnerID=40&md5=57781814f30f3f2f85b0db05ecf3b422

[6] A. Aslam Shaikh, A. Anil Pradhan, A. Mahesh Kotasthane, S. Patil, and S. Karuppanan, "Comparative analysis of Basalt/E-Glass/S2-Fibreglass-Carbon fiber reinforced epoxy laminates using finite element method," *Mater Today Proc*, vol. 63, pp. 630–638, Jan. 2022. https://doi.org/10.1016/J.MATPR.2022.04.385

[7] Z. Gürdal, R. T. Haftka, and P. Hajela, "Design and optimization of laminated composite materials," p. 337, Accessed: Dec. 21, 2023. [Online]. Available: https://www.wiley.com/en-us/Design+and+Optimization+of+Laminated+Composite+Materials-p-9780471252764

[8] S. Dong, C. Li, G. Xian, Z. Zhao, X. Zhang, and Q. Yun, "Environmental impact assessment of aircraft elevator made with new lightning protection material; [使用新型雷击防护材料的飞机升降舵环境影响评价]," *Journal of Zhejiang University: Science A*, vol. 23, no. 9, pp. 669 – 682, 2022. https://doi.org/10.1631/jzus.A2200105

[9] I. Bianchi, A. Forcellese, M. Marconi, M. Simoncini, A. Vita, and V. Castorani, "Environmental impact assessment of zero waste approach for carbon fiber prepreg scraps," *Sustainable Materials and Technologies*, vol. 29, p. e00308, Sep. 2021. https://doi.org/10.1016/J.SUSMAT.2021.E00308

[10] E. Peterson, "Technical Challenges to Adopting Large Scale Additive Manufacturing for the Production of Yacht Hulls," *Advances in Intelligent Systems and Computing*, vol. 1269, pp. 15–20, Jan. 2021. https://doi.org/10.1007/978-3-030-58282-1_3

[11] I. Bianchi, A. Forcellese, S. Pappadà, A. Salomi, and G. Zanzarelli, "Numerical analysis of flexural behaviour of nautical components in CFRP composite," *Procedia CIRP*, vol. 118, pp. 805–809, Jan. 2023. https://doi.org/10.1016/j.procir.2023.06.138

[12] S. Castegnaro *et al.*, "A bio-composite racing sailboat: Materials selection, design, manufacturing and sailing," *Ocean Engineering*, vol. 133, pp. 142–150, Jan. 2017. https://doi.org/10.1016/j.oceaneng.2017.01.017

[13] G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, and B. Weidema, "The ecoinvent database version 3 (part I): overview and methodology," *International Journal of Life Cycle Assessment*, vol. 21, no. 9, pp. 1218–1230, Sep. 2016. https://doi.org/10.1007/S11367-016-1087-8/FIGURES/7

[14] Y. S. Song, J. R. Youn, and T. G. Gutowski, "Life cycle energy analysis of fiber-reinforced composites," *Compos Part A Appl Sci Manuf*, vol. 40, no. 8, pp. 1257–1265, Aug. 2009. https://doi.org/10.1016/J.COMPOSITESA.2009.05.020

[15] A. Forcellese, M. Marconi, M. Simoncini, and A. Vita, "Life cycle impact assessment of different manufacturing technologies for automotive CFRP components," *J Clean Prod*, vol. 271, p. 122677, Oct. 2020. https://doi.org/10.1016/J.JCLEPRO.2020.122677