



ORIGINAL RESEARCH ARTICLE

Development and Life Cycle Analyses of Carbon Fiber Reinforced Polymer Tubular Parts for Metal Replacement in Aerospace Applications

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Reducing the weight of aircraft components is a key strategy to improve fuel efficiency and reduce greenhouse gas emissions. Innovative materials such as carbon fiber reinforced polymers (CFRPs) and manufacturing techniques represent a possible solution for improved sustainability in the aerospace sector. In this context, this paper presents the design and the evaluation of the environmental and economic impacts of a CFRP tubular structural component, employed for supporting passenger seats of commercial aircraft, realized with the innovative FW process. At first, a simulation of the winding process was conducted to define the component layers, and then a FEM analysis was performed to identify the optimal layering of the tubular structure to support the defined loads. Subsequently, environmental and economic impacts were evaluated by means of life cycle assessment and life cycle costing methodologies. The comparison between the CFRP tubular structure and traditional aluminum alternative was conducted to identify the most sustainable solution. The analysis showed that the CFRP tubular component resulted in lower environmental impacts than the traditional alternative (i.e., about 70% lower considering the whole life cycle) mainly due to the reduced weight. However, the cost evaluation identified the CFRP alternative as the most expensive solution, with production cost 40% higher than the aluminum alternative.

Keywords CFRP, filament winding, LCA, LCC

Abbreviations

Al	Aluminum
CED	Cumulative energy demand
CF	Carbon fiber
CFRP	Carbon fiber reinforced polymers
FEM	Finite element method
FU	Functional unit
FW	Filament winding
GWP	Global warming potential
LCA	Life cycle assessment
LCC	Life cycle costing
LCI	Life cycle inventory
LCIA	Life cycle impact assessment

1. Introduction

The use of carbon fiber reinforced polymers (CFRP) is significantly growing in many industrial applications, such as in aerospace, automotive, and construction ones (Ref 1). This is due to their high mechanical performance combined with low weight. CFRP components represent a valuable solution in many structural applications since they can provide a weight reduction with respect to traditional alternatives. Composite materials have revolutionized the space industry due to their multifunctional, multi-directional and tailorable properties that can sustain the extreme environment of outer space (Ref 2-5). Many manufacturing processes can be suitable to produce CFRPs components; most of them strongly rely on manual

labor and are associated with long production time and high costs. Among the possible manufacturing technologies, Filament Winding (FW) is an automated production process that allows to realize CFRP axisymmetric structures (Ref 6). In addition, CFRP components obtained with filament winding technique are characterized by excellent mechanical properties in terms of strength and stiffness, and fatigue resistance (Ref 7-11).

Filament wound CFRP tubular components are manufactured by winding towpreg material around a rotating mandrel along program-controlled trajectories. The component is then cured in an oven or autoclave to harden and reach its final strength (Ref 12, 13). Several processes and geometrical

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parameters can affect the mechanical properties of wound components such as winding angles and mandrel coverage (Ref 14-17). The choice of the geometrical parameters, along with the composite material anisotropy and possible defects due to the production process (e.g., fiber path intersection and uneven thickness), makes the design phase of filament wound component a complex and time-consuming issue.

Computer aided process simulation and design tools have been developed and proved to be an effective approach for composite design (Ref 18). Such methods allow to predict and optimize the design and process variables to obtain composite parts that fulfill structural requirements while keeping parts weight as low as possible. In an environmental sustainability perspective, weight reduction is a crucial requirement in many applications (e.g., for transport sectors); in fact, lower weight can be associated with an increase in vehicles efficiency and a reduction in fuel use, cost and environmental impacts.

In scientific literature, several studies focused on sustainability and cost assessment of composite parts can be found (Ref 19-25). Numerous studies investigated traditional composite technologies mainly based on manual labor (e.g., autoclave, compression molding, vacuum infusion...) (Ref 26, 27) However, innovative and automated composite production processes are also worth investigating as they can provide higher productivity and possible cost savings. For what concerns FW, studies evaluated the possibility of using sustainable materials, mainly focusing on structural and performance aspects and without carrying out Life Cycle analyses (Ref 28-30) Rasheed et al (Ref 31) compared the environmental and economic impacts of glass fiber filament wound parts to those of pultruded ones. However, the sustainability and cost of CFRP filament wound components needs additional investigation and comparison with traditional alternatives. For instance, the use of wound composites to replace traditional metal components should be studied to assess the applicability of the innovative materials and their possible benefits. This is required to promote sustainable development of the aerospace sector and to help the material selection process. In addition, in an integrated approach and in a design for environment perspective, a direct correlation between composites design and sustainability could be interesting on a scientific level and represent a useful industrial tool. As a matter of fact, it is important to combine sustainability aspects with structural criteria to ensure that the products fulfill the design requirements but, at the same time, keep their carbon footprint low.

In this context, the present paper aims at designing and evaluating the environmental and economic impacts of a CFRP tubular structural component employed for supporting passenger seats of commercial aircraft (Ref 32) The study fills the literature gap by providing a comparison between traditional and filament wound aerospace parts and presenting an integrated assessment that includes structural and sustainability aspects. From a scientific perspective, this study also helps to highlight the strengths and weaknesses of each solution, thereby guiding future research and providing a deeper understanding of innovative technologies and their associated impacts.

Simulations of the winding process and FEM analyses were performed to identify an optimal composite layering of the tubular structure to support the defined loads. Subsequently, environmental and economic impacts were evaluated by using life cycle assessment (LCA) and life cycle costing (LCC)

methodologies. A comparison between the CFRP tubular structure and traditional aluminum alternative was conducted to identify the most sustainable solution and improvement possibilities (Ref 33)

The paper is organized as follows: After this introduction (section 1), details are presented regarding the CFRP tubular component design phase (section 2.1). Process and structural simulation software were employed. After that, the steps followed to conduct the environmental and cost analyses are presented (Section 2.2-2.3). Section 3 presents the results, first for the design phase and then for the LCA and LCC analyses. Note that the life cycle analyses employed the design results as input data. Lastly, conclusions and future developments are presented in section 4.

2. Materials and Methods

2.1 Design Phase

The first step of this study consisted in the design of a CFRP tubular structure applied under the passenger seats of commercial aircrafts for their support (Fig. 1). The aluminum commercial product that is produced by the industrial partner has a weight equal to 1.23 kg. The goal of this first phase is to define the composite layering to be used which can provide weight reduction while keeping the same structural performances. The defined tubular component has a length equal to 1430 mm and a constant diameter of 50 mm. In addition, since the thickness of the commercial Al tubular component is about 3 mm, the aim is to obtain a CFRP tubular component characterized by a thickness lower than this value.

The constraints and loads conditions applied to the structure, as well as the component dimensions previously defined were provided by industrial partner. The part is subjected to two concentrated loads equal to 6505 N applied in correspondence of the center of two of the three seats, which represent the weight of passengers in the worst condition in which the load is



Fig. 1 Representation of the tubular component

unbalanced on one side of the tubular component. In addition, a distributed load over the entire length equal to 1982 N/m is considered as the weight of the entire structure, which is composed by the three seats.

Two fixed translation constraints are considered and applied at 1/3 and 2/3 of the structure length (Fig. 2). The considered loads lead to a conservative evaluation since they represent the worst-case condition where two people are seated, respectively, in the middle and at one end.

The composite tubular component was produced by filament winding process using a towpreg with 68%wt carbon fibers and 32%wt epoxy resin matrix; starting from the single constituent datasheets, the mechanical properties of the total composite were calculated using the mixture rule (Table 1).

An iterative procedure involving the use of two software was employed to define the composite layering, namely the number and the orientation of layers (Ref 34) By means of CADWIND software it was possible to create virtual models of composite layers, by simulating winding with different angle values (Ref 35) Given input data related to the raw materials (e. g., fiber width, volume fraction...) the software allows to simulate the entire filament winding process and calculate fiber paths and winding patterns. In addition, CADWIND allows the creation of meshed models that represent the composite part, which can subsequently be simulated in Finite Element Method (FEM) software. The models created in CADWIND were imported in FEM software (Siemens NX) to simulate their structural response in a static structural solution (SOL 101). The previously defined loads and constraints were applied to the structure to obtain the stress and strain in each composite layer (Fig. 3). The maximum stress, strain (i.e., max strain equal to 0.008) and Tsai-Wu criteria were employed to determine if the chosen layering satisfied the structural requirements. The final layering was obtained iteratively, by analyzing the output of FEM simulations and changing the layer number and the orientation consequently. The design phase was also essential for the Life Cycle Analyses as it provided primary data concerning the component material quantity and production process.

2.2 Life Cycle Assessment

To evaluate the environmental impacts related to the CFRP tubular component and to compare them with those of a traditional Al one, the LCA methodology based on the UNI EN ISO 104040 – 14044 standards, was used. The main phases of the LCA procedure are: 1) Goal and scope definition; 2) Life Cycle Inventory (LCI); 3) Life Cycle Impact Assessment (LCIA); 4) Interpretation of results.

2.2.1 Goal and Scope Definition. The scope of the LCA analysis is to define if the use of CFRP instead of aluminum to realize the tubular component represents a more environmentally sustainable solution. The functional unit (FU) is defined as the production of a tubular component with length and diameter equal to 1430 mm and 50 mm, respectively, and able to withstand the loads described above. The present analysis follows a “from cradle to grave” approach. Figure 4 shows all phases included within the system boundaries of the study. Two different scenarios were analyzed: *Scenario 1* concerns the production of a CFRP tubular component with a FW process and *Scenario 2* includes the production of an aluminum tubular component. The phases included in the former are raw materials extraction and production, prepregging phase, aluminum mandrel production, FW and curing processes, use phase and end-of-life phase which included a landfill disposal. For the latter, the phases considered are raw aluminum extraction, machining and drilling processes, use phase and an 80% Al recycling as end -of-life phase.

2.2.2 Life Cycle Inventory (LCI). Different data sources were considered to collect Life Cycle Inventory data: Primary measured data and secondary data retrieved from literature and Ecoinvent commercial database were employed (Ref 36) The quantities of carbon fiber (CF) and epoxy resin were calculated based on the design phase output. It was considered that the towpreg is composed by 68%wt of CF and 32%wt of epoxy resin. CF production as well as transport of both epoxy and CF was modeled according to literature (Ref 37) Epoxy resin production model in Ecoinvent database was used. Energy consumption related to preimpregnation phase was retrieved from literature (Ref 38) and allocated to the tubular component considering its weight. Consumable materials and energy consumption of curing process were retrieved from literature (Ref 37) and allocated to the FU considering its weight. The energy consumption related to the filament winding process was retrieved from literature (Ref 38) The quantity of aluminum and the energy consumption required to realize the mandrel used for the filament winding process were directly calculated based on data provided by industrial partner. It was assumed that the mandrel lifespan is equal to 1500 cycles. As far as Scenario 2 is concerned, the quantity of raw aluminum and material removed with machining and drilling processes was provided by the industrial partner. For both scenarios, the use phase is related to the consumptions needed by a passenger aircraft in its lifespan allocated to the component weight. These consumptions were calculated considering the distance traveled by a passenger aircraft during its lifespan and the weight of the component. Data related to this phase were retrieved by literature (Ref 39, 40) an aircraft lifespan of 25 years and an

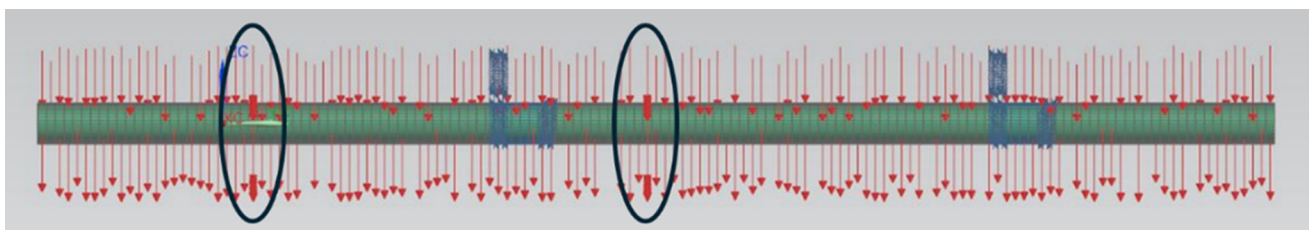


Fig. 2 Loads and constraints representation in Siemens NX; concentrated loads are circled

Table 1 Mechanical properties of the considered materials

	Carbon fiber	Epoxy resin	Composite material
Elastic modulus, E	230 GPa	3500 MPa	131 GPa
Ultimate tensile strength, σ_R	4900 MPa	73 MPa	2790 MPa
Density, ρ	1.8 g/cm ³	1.1 g/cm ³	1.6 g/cm ³

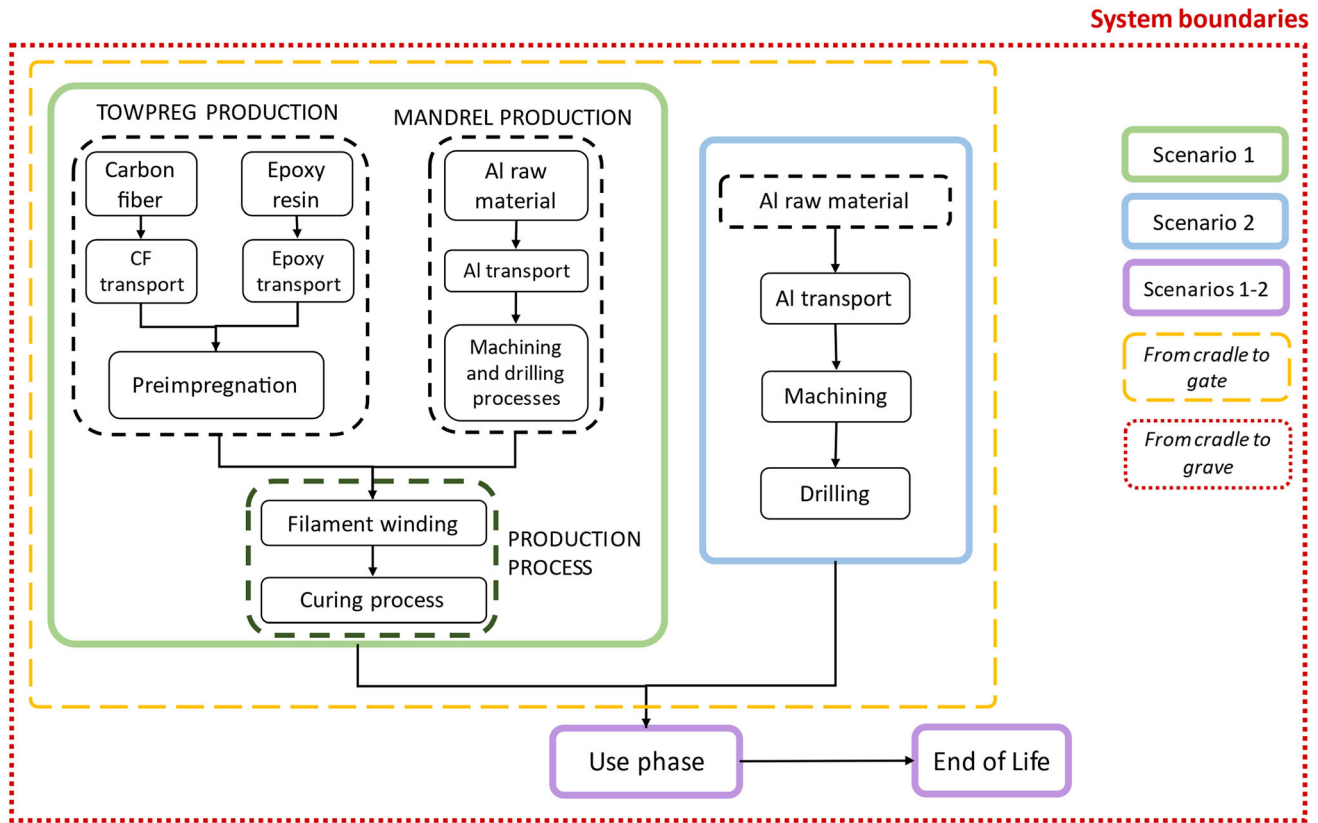


Fig. 3 System boundaries of the investigated scenarios

average traveled distance equal to 40000000 km were considered. The impacts related to the use phase of a passenger aircraft considered in this analysis were modeled in Ecoinvent.

Table 2 reports all input data of the CFRP one. Data related to Al component production (Scenario 2) are similar to those of the aluminum mandrel production (parts with same dimensions); the main difference is that impacts related to mandrel production were divided for its lifespan (1500 cycles) to be allocated to the functional unit.

2.2.3 Life Cycle Impact Assessment (LCIA). A comprehensive view of the environmental loads of the two analyzed scenarios can be obtained by considering different environmental indicators and analysis methods. This study considered different impact assessment categories: Global Warming Potential (GWP), ReCiPe categories and Cumulative Energy Demand (CED). SimaPro software was used to model the scenarios and translate of inventory data into possible effects on the environment.

2.3 Life Cycle Costing

The present LCC analysis aims at quantifying the costs associated with a CFRP tubular component life cycle and

compare it with a metallic one currently on the market. By considering CFRP composite materials, LCC considers initial, operative, maintenance, disposal, and recycling costs. This analytical approach allows the determination of various opportunities of savings and the optimization costs in the long run. The LCC analysis considers the same FU of the environmental sustainability assessment. For the CFRP component, both primary and secondary data were employed for the cost evaluation, while the metallic component cost assessment was based on primary data provided by the industrial partner. To evaluate the costs of the mandrel necessary in filament winding process, and aluminum component Lean Cost software was used. Lean Cost is a software solution for costing based on an analytical calculation approach. It allows the optimization of product costing and automatic quotation generation to improve the competitiveness and sustainability of products. Initially, the CAD model was loaded, and the parts material was defined (aluminum 6XXX). The next step was the modeling of the production processes. After the strategies selection, the raw material starting geometry and dimension were defined. Finally, the production process was analyzed, and it was possible to change, add or remove other phases and define process parameter. Machining and drilling processes of the aluminum

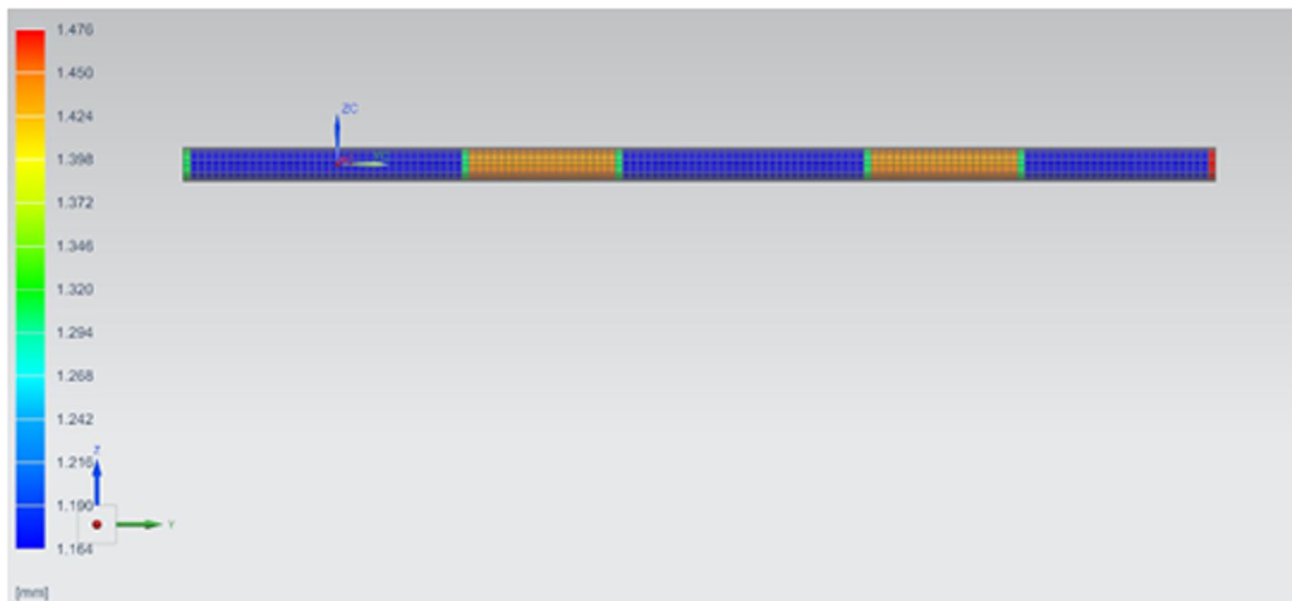


Fig. 4 Thickness distribution along the component

Table 2 LCI input data of CFRP tubular component

Phase	Element	Quantity	Unit	References	
Material	Carbon fiber	0.286 ($V_f=57\%$)	kg		
	Epoxy resin	0.134 ($V_m=43\%$)	kg		
Prepregging	Energy consumption	40	MJ/ kg of composite	(Ref 37)	
Filament winding	Energy consumption	2.32	kWh/kg of composite	(Ref 38)	
Curing process	Vacuum bag (PA66)	0.013	kg	(Ref 26)	
	Breather (PET)	0.01	kg		
	Release film (PTFE)	0.001	kg		
	Release agent (Organic solvent)	0.0008	kg		
	Energy consumption	0.45	kWh		
	Mandrel (Lifespan=1500 cycles)	Aluminum	1.4	kg	
		Al removed (machining)	0.165	kg	
Al removed drilling		0.0075	kg		

tubular component were considered in Lean Cost software to evaluate the cost. The CFRP component cost was calculated using a spreadsheet by modeling all the production phases; differently from the LCA, the impregnation phase was not included and commercial towpreg cost per kg was considered.

As concerns the FW process, the major cost factors are energy, labor, material, and depreciation costs. Given the quantity of CFRP necessary to realize the component, the unitary energy consumption per kg of FW (Ref 38) and unitary energy cost, it is possible to determine the total energy cost. Labor cost was calculated considering the process time and the hourly labor cost; one expert operator, and a specialized assistant were required to carry out the process. In this phase the setup time was considered half of the winding process time. The material cost is derived from the commercial towpreg cost per kg of CFRP and the weight of the material necessary for the component. Finally, the depreciation cost of the filament winding machine was calculated considering its service life, its purchase, and its maintenance cost (considered equal to 10% of the filament winding machine cost).

For the curing phase, the relevant cost factors are energy, labor, material, and depreciation costs. Given the energy

consumption of the curing process (Ref 26) and unitary energy cost was calculated the cost of the autoclave curing process. Labor time cost was calculated considering the time required for molding and demolding the vacuum bag and hourly labor cost. In the material cost are considered the cost of consumable materials for vacuum bag. In particular, sheets of Nylon 6,6 (vacuum bag), polyethylene terephthalate PET (breather), Polytetrafluoroethylene (release film) and liquid solvent (release agent). Finally, it was considered the depreciation costs of the autoclave considering the investment cost, maintenance cost, and service life.

For what concerns the EoL phase, the landfill disposal was considered for CFRP component material and vacuum bag consumable materials. For the aluminum mandrel and tubular component, recycling with an 80% efficiency was considered (Ref 41) To quantify EoL costs the unitary disposal costs were multiplied by the weight of waste materials.

However, Lean Cost software was used to quantify mandrel costs. Subsequently, the so obtained value was divided for the number of winding processes during the mandrel service life (1500 cycles).

The cost values associated with these phases are reported in Results section in Table 4.

3. Results and Discussion

3.1 Design Phase

Since the aim of this study was to obtain a lightweight structure as possible which would support the required loads, initially the FEM analyses were conducted by considering a low number of layers with a winding angle equal to 20°. This value represents the best trade-off between the minimization of thickness according to netting analysis and the feasibility of the FW process (Ref 42). As a matter of fact, lower values of winding angle are not commonly used in industrial practice. The first stratifications simulated were composed only by different number of 20° windings layers: This provided a high tensile stiffness, but the FEM simulations showed critical zones at the hinges. This is related to the anisotropic properties of the towpreg: High properties are obtained along fibers orientation direction. For this reason, it was necessary to add some hoop windings to reinforce the cross direction to the one of fibers orientation in correspondence to the most stressed areas. After several iterations, the final layering was defined by three layers with 20° winding angle and a reinforcement layer with 85°

winding angle placed in correspondence of the most stressed areas (around the hinges).

In this last case, the values identified as the maximum stress and strain in the static structural simulation were, respectively, equal to 1171 MPa and 0.007. These values are lower than the ultimate tensile strength and strain of the considered composite material (2790 MPa and 0.008). Similarly, infinite life is expected since the resulted maximum stress is below the fatigue limit.

This layering is constituted by 4 total layers, which led to an average structure thickness of about 1.2 mm along the structure. For the reinforced areas, a maximum thickness value of 1.4 mm was obtained. Figure 5 shows the thickness distribution along the tubular component length and highlights the location of the reinforcement layers.

In addition, the accumulation phenomena which occurs during FW process (i.e., at the ends of the structure, in the turning zones) involved in a slight variation of the component thickness can along its length.

The final weight of the CFRP component is of 0.420 kg, approximately half of commercial aluminum alternative. This highlights the potential of CFRP in weight reduction.

3.2 LCA Results

Table 3 reports the results analyzed by GWP (in terms of kg CO₂ eq) and CED (in terms of MJ) impact categories for

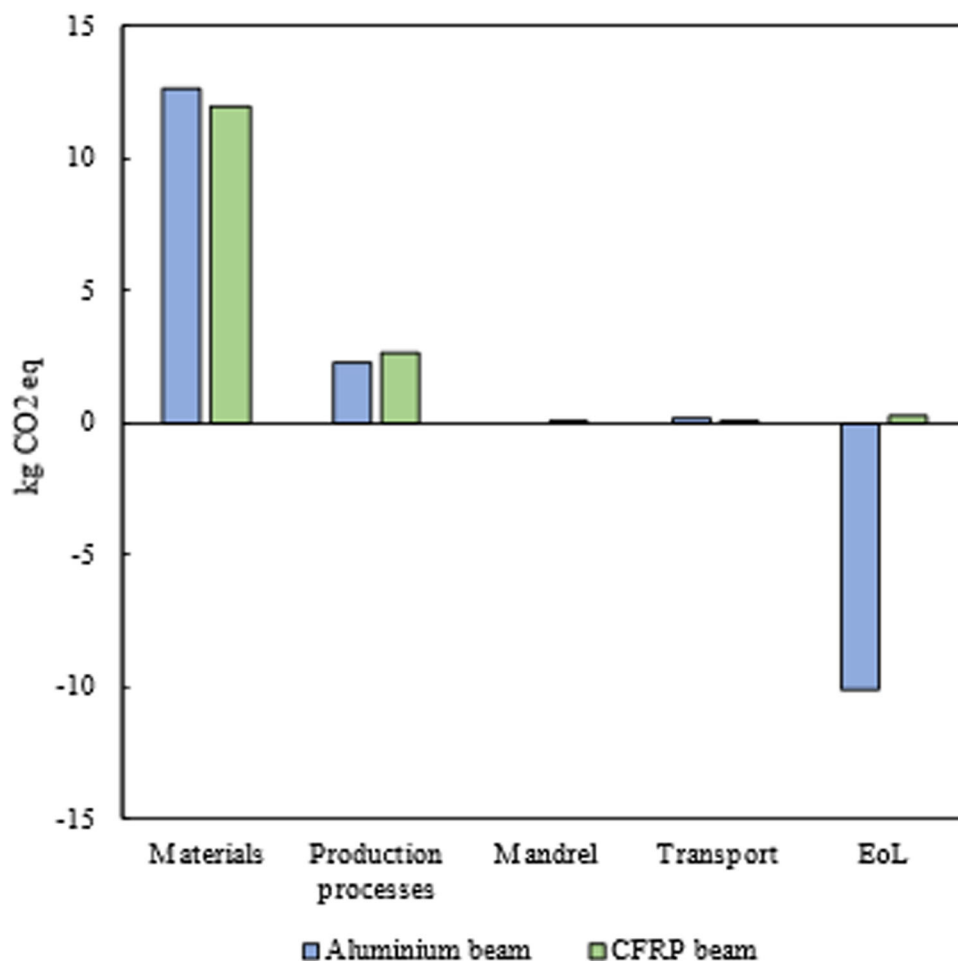


Fig. 5 GWP results of materials, production processes and EoL phases of two analyzed scenarios

Table 3 GWP results of analyzed scenarios

		Unit	Total	Materials	Production processes	Mandrel	Transport	Use phase	EoL
GWP	CFRP component (Scenario 1)	kg CO ₂ eq	12214.19	12.01	2.60	0.01	0.03	12199.82	0.26
	Al component (Scenario 2)		40669.25	12.61	2.27	0.00	0.18	40664.274	-10.09
CED	CFRP component (Scenario 1)	MJ	183094.25	204.94	54.29	0.16	0.55	182834.2	0.16
	Al component (Scenario 2)		609521.74	218.64	27.89	0.00	2.97	609447.16	-174.92

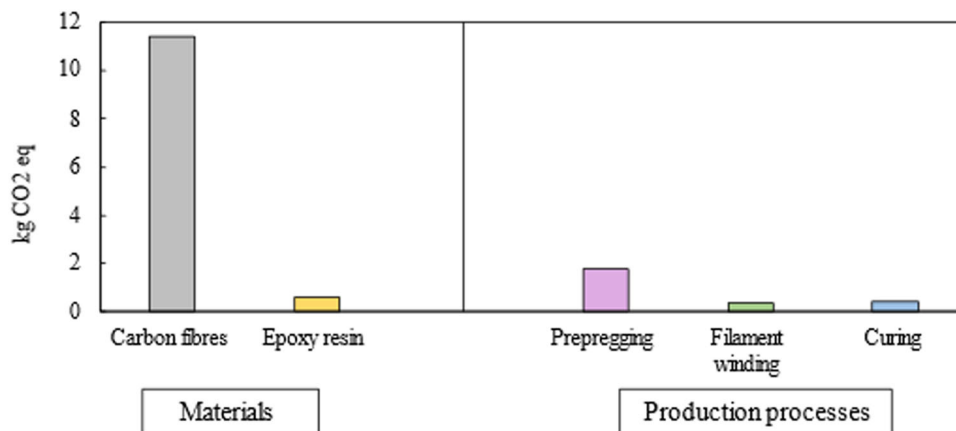


Fig. 6 Environmental impacts of materials and production processes phases of Scenario 1, GWP 100

Scenario 1 and Scenario 2. A relevant difference can be observed between the two scenarios: The total environmental impacts related to the CFRP component are about a quarter of those related to the Al one. This result is almost completely due to the use phase which is related to the consumption of a passenger aircraft during its lifespan allocated to the component weight. The lower weight of the CFRP component results in a reduction in consumptions during the use phase and, therefore, in lower environmental loads. Negligible impacts values are obtained for mandrel and transport phases.

Table 3 shows similar trend results for the two considered impact categories. The GWP results are showed in Fig. 6.

Figure 6 shows that the materials phase of the Scenario 1 is slightly more impactful than the one of Scenario 2. This result is related to the quantity of raw material used, which is equal to 1.40 kg of Al (Scenario 1) and 0.42 kg of CFRP (Scenario 2). This highlights the higher environmental unitary impacts of CFRP which are about 28.60 kg CO₂ eq per kg with respect to the ones related to the Al which amount 9.01 kg CO₂ eq per kg. However, the strong weight reduction makes composite raw materials impacts lower than the traditional counterpart.

The environmental load related to the production process of the CFRP tubular component is slightly greater than those generated by the Al one. The main contribution to Al component production is related to the machining processes. The higher environmental load of CFRP component production with respect to the Al one production is due to the composites production processes which are energy intensive and require the use of consumable materials.

As regards the end-of-life phase a consistent difference between two scenarios is observed: Al recycling considered in Scenario 2 results in negative environmental impacts (i.e., associated to the reduction in virgin material use). This leads to

a reduction in total environmental impacts of the Al tubular component. On the other hand, the composite part is considered to be sent to landfill disposal.

A particular focus was given to materials and production processes phases of Scenario 1, as shown in Fig. 7. It is shown that carbon fibres are associated with high environmental impacts of about 95% of the materials total carbon footprint, while epoxy resin only account for 5% of the materials total carbon footprint. As concerns the production processes, the prepregging phase provides greater environmental impacts than the filament winding and curing processes. This result is mainly due to the amount of energy required by this process. The last two cited processes give negligible impacts, especially FW which resulted a sustainable process, involving only 0.372 kg CO₂ eq for 0.420 kg of CFRP. The curing process provides slightly higher impacts than the FW process which result about 0.449 kg CO₂ eq. However, these obtained values are much lower than the one related to materials phase and to carbon fibres: The total environmental load related to all the production processes (prepregging, filament winding and curing) is about 78% lower than the one related to the materials phase.

ReCiPe methodology was also used to obtain LCA results in terms of 18 midpoint categories (showed in Fig. 8). It highlighted a similar trend result with respect to the ones previously observed with GWP and CED: The use phase gives the highest percentage contribution to the total impact for all considered impact categories.

Figure 8 highlights the obtained results of all phases included within system boundaries except for the use phase. The materials phase results the most impactful one for both scenarios in all considered impact categories and this outcome is in line with the results analyzed with GWP and CED categories. A difference between the two scenarios can be

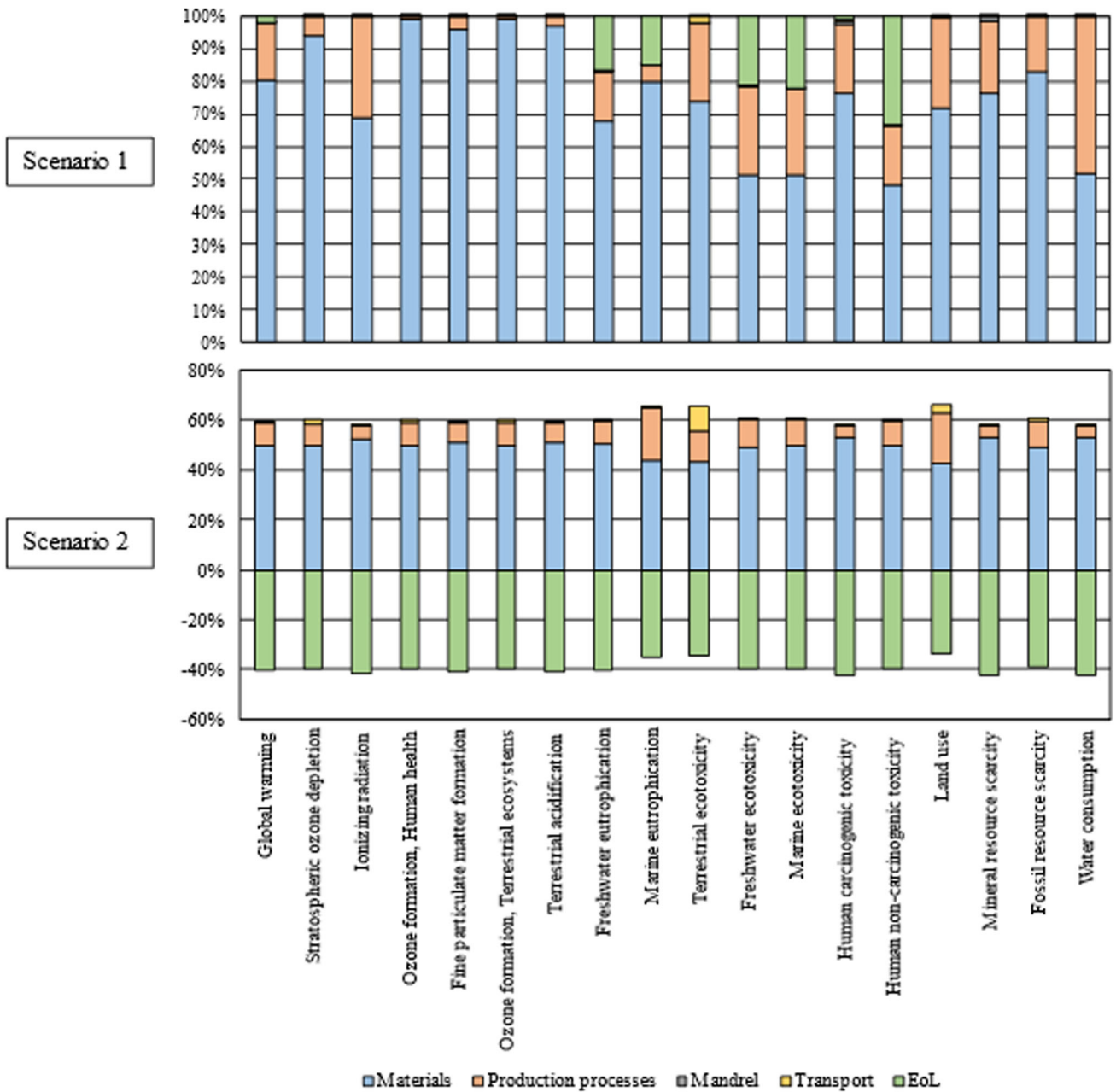


Fig. 7 LCA results analyzed with ReCiPe methodology

observed: the percentage contribution of end-of-life phase is negligible for almost all impact categories in Scenario 1, while it is consistently negative in Scenario 2. This results in an important reduction of total environmental impacts thanks to the recycling and the recovery of the aluminum in the Scenario 2; the same outcomes are not obtained in Scenario 1 since a landfill disposal of composite material was considered.

It is interesting to notice that the end-of-life phase in Scenario 1 gives relevant percentage contribution for “Freshwater eutrophication,” “Marine eutrophication,” “Freshwater ecotoxicity,” “Marine ecotoxicity” and “Human non-carcinogenic toxicity” impact categories. This result could be related to the emissions during the landfill disposal which are particularly harmful for the marine and the freshwater environments. In

addition, it could be observed that the transport phase gives a slight but noticeable percentage contribution for the “Terrestrial ecotoxicity” impact category and this is probably due to the terrestrial emissions related to the transport of the AI from the supplier to the user. As a general outcome, all impact categories of both considered scenarios show a similar results trend, in terms of percentage contributions of the analyzed phases.

Since the uncertainties of input data can relevantly affect the LCA results, a sensitivity analysis was also carried out for Scenario 1 to evaluate how the total environmental impacts can vary as the input data changes. The focus of the analysis was given to relevant impact variables of Scenario 1, such as the use phase, the materials and the production process. The considered variation range within they can vary is equal to -100% and+

100%, since it is representative of the sensitivity of the total impact to the variation of an input variable. Table 4 reports the impact range of the input data in terms of kg of CO₂ eq.

From Table 4 emerged that the use phase is the most sensitive to the variation of the input data. Higher use phase impacts can be related to higher parts weight or longer service life; this strengthens the need for weight reduction and design optimization to reduce fuel consumption and further highlights the industrial relevance of the proposed combined approach. The analysis results solid as the same service life distance was considered for both scenarios. On the other hand, the use of filament wound component for different applications (e.g., non-

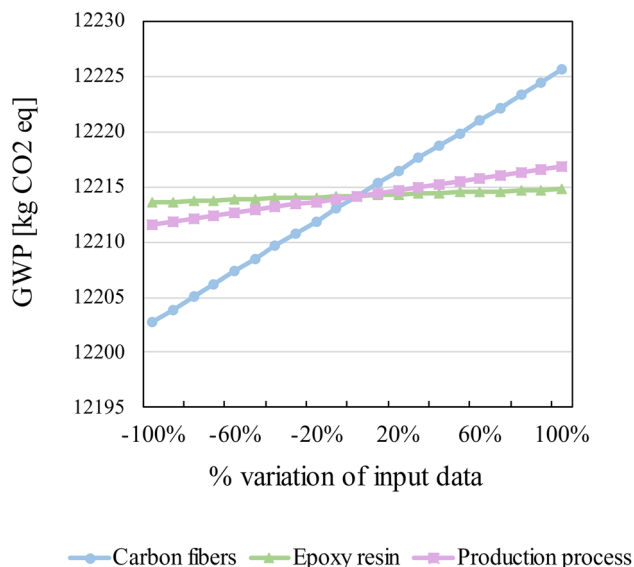


Fig. 8 Sensitivity analysis results

Table 4 Data variation ranges in terms of GWP100

	Variation range, kg CO ₂ eq
Epoxy	0÷1.2
CF	0÷22.8
Production process	0÷5.2
Use phase	0÷24398.6

Table 5 LCC results for each phase of scenario 1

Mandrel		
Mandrel cost (calculated by LeanCost)	26.63	€
Filament Winding phase		
Energy cost	0.14	€
CFRP towpreg cost	15.54	€
Labor cost	40	€
Machining depreciation	38.55	€
Mandrel (for each cycle of service life)	0.02	€
Curing phase		
Energy cost	0.06	€
Labor cost	10	€
Consumable material for vacuum bag	0.25	€
Autoclave depreciation	27.41	€
EoL phase		
CFRP (towpreg)	0.80	€
Al (mandrel)	-0.001	€

transport related) could strongly reduce their use phase impacts; however, in that case, the advantages offered by the reduced weight in CFRP would lower and traditional alternatives such as aluminum part would be the best solution. The use phase impacts are about 4 order or magnitude higher than the other production phases. Hence, Fig. 8 focuses only on the impacts variation of the carbon fibers, the epoxy resin and the production process impacts. Figure 8 highlights that the carbon fibers phase is the most sensitive to the input data variation with respect to the other phases; hence, reduction of CF impacts can be a significant goal to reduce the sector carbon footprint. A lower outputs variation range is achieved by the production process phase; for instance, a variation in manufacturing phase impacts of about -50% would lead a reduction in parts impacts equal to -9% (that would be the case of the use of more sustainable energy mixes). The lowest sensitivity to the input variation is obtained by the epoxy resin production, with little influence on total results variability.

3.3 LCC Results

LCC results for both tubular components are presented in Tables 4 and 5. The total costs are divided into different contributions: the machinery cost includes the purchase and the maintenance of the machine, and the depreciation cost attributable to each component; Equipment cost includes the price of the tool used during the machining; Material cost includes the cost of the material for each Scenario, and the costs for consumable materials; Energy cost includes energy consumption costs during all the processes; Labor cost cover the cost of the manpower necessary during the manufacturing processes; EoL cost includes the cost for the disposal of the non-recycled materials, and for aluminum recycling. In Table 6 the cost breakdown for each scenario is reported.

In the first Scenario the highest cost contribution is attributed to machinery purchase (i.e., 65.69€); specifically, the large contribution of this category is due to of high cost of filament winding machine and autoclave and their high maintenance cost. Another significant cost factor is labor (50 €), which requires a high level of expertise for the filament winding process and molding and demolding phases of autoclave curing. However, labor contribution is significantly lower with respect to more manual production processes for composite parts (Ref 43) Despite the high unitary cost of composite material, it does not represent a major cost item in Scenario 1; this is due to the low quantity of CFRP used for the tubular component. Finally, the costs of energy, equipment and EoL are negligible; overall, the filament winding process and part curing are characterized by relatively low energy use. As far as the mandrel is concerned, its costs are negligible since it can be reused several times before being recycled. The total

Table 6 LCC results for CFRP and Al tubular components

Cost categories	CFRP component, €	Al component, €
Machinery cost	65.96	13.11
Labor cost	50.00	5.69
Energy cost	0.20	5.60
Material cost	15.54	57.89
Equipment cost	0.27	0.48
EoL cost	0.80	-4.15

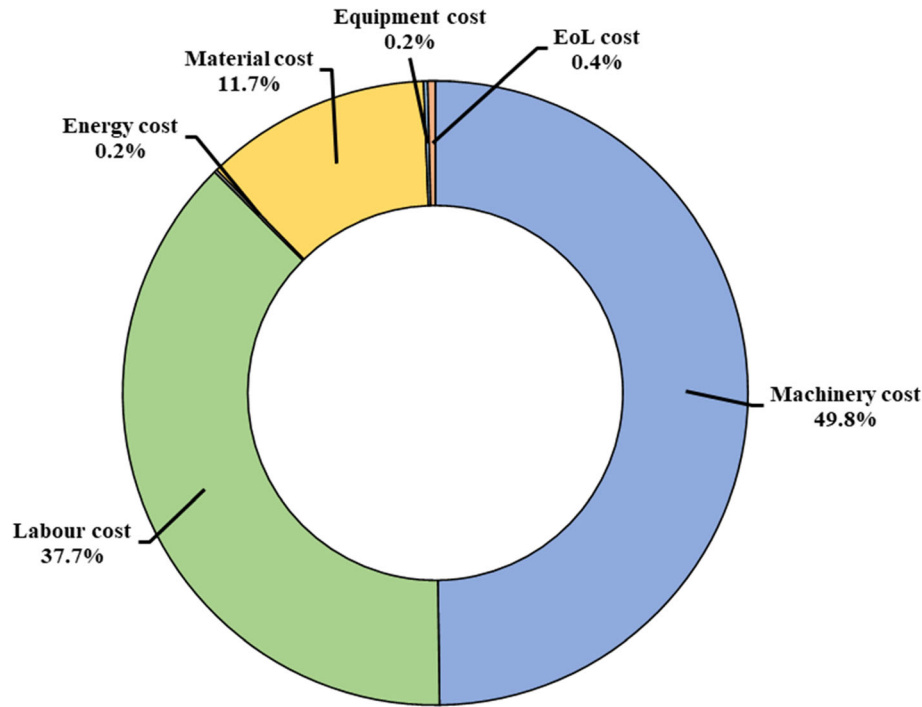


Fig. 9 Scenario 1 cost breakdown

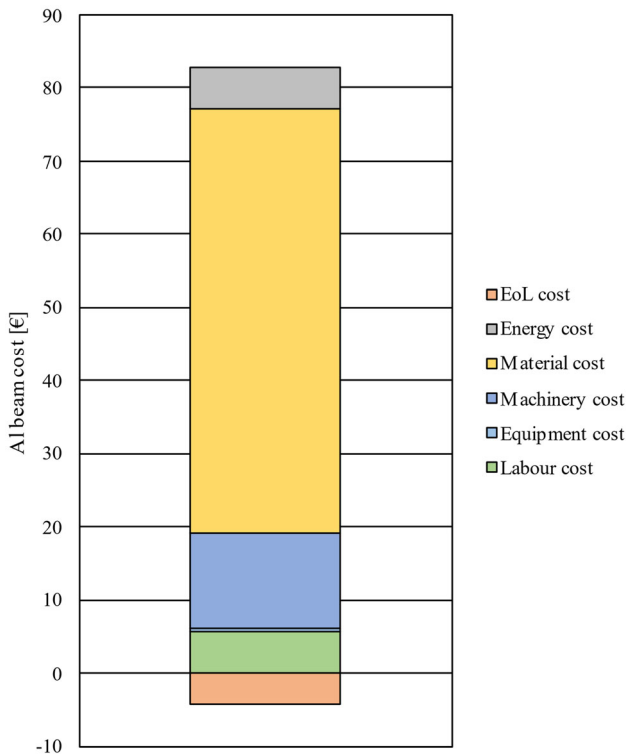


Fig. 10 Scenario 2 cost breakdown

cost is the sum of all cost factors and amounts to 132.60€. The percentage contribution of Scenario 1 costs is shown in Fig. 9.

On the other hand, the highest cost contribution of Scenario 2 is attributed to raw material (i.e., 57.89€). In fact, the

aluminum tubular component is heavier than its composite counterpart; in addition, aluminum material excess is required because of waste generated during chipping operations. Labor cost is lower than Scenario 1, since the manufacturing process to realize aluminum component requires a lower cycle time with respect to those needed by the production of the CFRP one. Like for Scenario 1, equipment cost is negligible; 5-axis machine tools are typically general purpose, and their purchase cost can be distributed on high number of manufactured products. In this Scenario, the EoL cost is negative, since it is considered that waste aluminum can be sold and then recycled. These costs were allocated to the functional unit considering the required production time and the machines service life. The total cost is the sum of all cost factors and amount to 78.62€. The cost breakdown, for Scenario 2, is shown in Fig. 10.

4. Conclusions

This paper presented the design and the life cycle analyses of a CFRP tubular component used for the support of passenger seats in commercial aircraft. In addition, a comparison between the CFRP component and a traditional Al beam was performed in terms of economic and environmental sustainability. The main outcomes are reported as follows:

- The final composite layering was defined as $[\pm 20_3]$ with two additional reinforcement layers with a winding angle equal to 85° located in correspondence of the two hinges. This layering allows to respect the defined stress and strain limits.
- The proposed composite design leads to a CFRP beam weight of 0.420 kg, that is less than half of the Al one (about 1 kg).

- The CFRP towbar resulted in lower total environmental impacts with respect to the Al one for all considered methodologies; in terms of GWP the resulting values are, respectively, equals to 12214.19 kg CO₂ eq and 40669.25 kg CO₂ eq. This is mainly due to the weight reduction and lower use phase emissions.
- The CFRP component total cost is 132.60 €, and it is higher than the traditional metallic beam realized in aluminum by approximately 40%. For Scenario 1 the main cost factor is the machinery cost (i.e., 49.8% of the CFRP total cost).
- Scenario 1 involves higher total costs, mainly due to the investment required for machinery, maintenance and the specialized labor involved. However, it offers advantages in terms of reduced material consumption and low energy impact.
- Scenario 2 has lower total costs, thanks to reduced labor expenses and the ability to recycle aluminum, which offsets overall costs. In Scenario 2 material costs are larger with respect to Scenario 1 due to the higher weight of the component, though the specific cost is lower.
- Although the CFRP beam resulted in the most expensive solution, it is a valuable alternative to the Al one in terms of mechanical performance and environmental sustainability.

The results highlight the significant potential of CFRP in reducing weight and carbon footprint in aerospace applications. The study is limited to a single composite manufacturing condition; hence, to expand the applicability and relevance of the results, other manufacturing technologies (e.g., autoclave molding, pultrusion...) and different polymeric matrixes and reinforcements (i.e., thermoplastic polymers and natural fibers) could be investigated. Experimental validations of the design phase will also be conducted and broadened to different aerospace sector components.

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