



Comparative life cycle assessment and cost analysis of autoclave and pressure bag molding for producing CFRP components

Alessio Vita¹ · Vincenzo Castorani¹ · Michele Germani¹ · Marco Marconi²

Received: 26 April 2019 / Accepted: 2 September 2019 / Published online: 11 September 2019
© Springer-Verlag London Ltd., part of Springer Nature 2019

Abstract

Composite materials are demonstrating the ability to face the challenge of competitive markets where high-performance, low costs, and reduced manufacturing time are mandatory. Vacuum bagging with autoclave curing is one of the most used manufacturing methods for carbon fiber composite parts. However, it shows some limitations, mainly due to manual operations and long processing time. Out-of-autoclave (OOA) methods, such as pressure bag molding (PBM), can lead to a strong reduction of the manufacturing time through the simplification of lay-up and curing phases. In this paper, a comparative analysis between the autoclave and the PBM processes has been performed, jointly considering both the economic and environmental aspects. An evaluation of the environmental impacts has been carried out following the standardized life cycle assessment (LCA) methodology. In addition, costs related to these two manufacturing techniques have been estimated through a parametric approach and successively compared. Different scenarios have been considered to take into account various production batches, mold manufacturing techniques, and end of life alternatives. The analyses show conflicting results demonstrating that a global optimum scenario does not exist and, depending on the chosen indicator and production batch, the best alternative varies. Considering only the environmental indicators, the autoclave process can be considered the most sustainable option, due to the lower consumption of energy.

Keywords Autoclave · Out of autoclave processing · Prepreg · Life cycle assessment · Cost analysis · Scenario analysis

1 Introduction

The market of composite materials is continuously growing due to the increasing number of industrial applications [1]. In the past, composite materials were limited to high-performance uses because of their high production cost, while nowadays, the advancement in manufacturing techniques has widened the application of such materials in several lightweight constructions [2]. As reported in literature [3], carbon composites are becoming cost effective alternatives in comparison to other standard materials. One of the driving markets for composites, especially carbon fiber reinforced polymers (CFRP), is the automotive industry [4]. Recently, the

increasing interest in the development of more efficient cars, high-range electric vehicles (EVs), and hybrid electric vehicles (HEVs) has forced companies to adopt composites for balancing the heavy battery weight. However, from a life cycle perspective, the relevant quantities of energy required during the manufacturing of raw materials (carbon fibers and matrices) nullify the beneficial effects of fuel savings [5, 6].

In the mass production sectors (e.g., automotive), costs and times of the traditional long fiber CFRP manufacturing process (i.e., autoclave) are not adequate [7]. Several out-of-autoclave (OOA) processes have been identified as the most promising solutions to overcome these limitations [8]. They can be divided in two main groups: (i) processes based on dry fibers, and (ii) processes based on prepregs.

Concerning the first group (i.e., based on dry fibers), the most common methods are resin transfer molding (RTM), resin infusion (RI), and their variants. RTM techniques, which exploit very high injection pressure, in face of high investment costs, can be used for producing high-performance components with a reduced lead time [9]. RI methods exploit a distribution media instead of a metallic counter-mold to

✉ Alessio Vita
alessio.vita@staff.univpm.it

¹ Università Politecnica delle Marche, Via Brecce Bianche, 60131 Ancona, Italy

² Università degli Studi della Tuscia, Largo dell'Università, 01100 Viterbo, Italy

compensate the low injection pressure. If compared to high-pressure RTM, this technique generally requires less expensive tools but leads to the production of parts with lower performances [10].

Concerning the second group (i.e., based on prepregs), vacuum bag only (VBO) methods exploit the atmospheric pressure for the compaction of laminates, while typically the prepreg cure takes place in an oven. The main weakness is related to the long processing time, needed for extracting gases from the laminate [11, 12]. Self-resistance electric (SRE) heating is another method conceived as an alternative to out-of-autoclave technology due to its characteristics of uniform heating, fast heating/cooling, low energy consumption, and low equipment investment [13]. In another family of methods, called pressure bag molding (PBM) [14], pressure is applied through the inflation of a flexible bag positioned over the prepreg preform and a heated metallic mold is used as a means to cure the resin [15]. As reported in Park et al. [16], PBM technique can be satisfactorily considered to replace the autoclave process and can be applied to manufacture low cost CFRP products. This makes the process very attractive from an industrial point of view even if the environmental impacts must be deeply investigated [17].

Given the increasing interest on sustainability themes, several recent literature studies are focused on the economic and/or environmental assessment of CFRP manufacturing methods. Concerning the environmental sustainability, Duflou et al. [18] estimated that the production of raw materials (fibers and matrices) represents more than 90% of the total impacts of a CFRP component. Suzuki et al. [19] reported that the impregnation phase for producing prepreg is the most energy-intensive phase in autoclave methods. Song et al. [20] carried out a cradle to grave life cycle assessment (LCA) of composite materials and estimated that the autoclave process requires two times the energy of the RTM process. Witik et al. [21], instead, presented the economic and environmental performances of different production methods (autoclave vs VBO and conventional RI vs microwave curing RI). Results show that autoclave is the most expensive and impacting process, while VBO is a useful solution to jointly reduce environmental impacts (10–20%) and manufacturing costs (6%). Other improvements can be obtained through the adoption of RI that leads to lower costs and lower impacts related to base material production (dry fibers vs prepreg). Similarly, a reduction of about 30% of total manufacturing costs has been observed by Tong et al. [22] who analyzed the production of an L-shape CFRP component by using OOA methods. In this case, the economic savings for smaller and simpler equipment balance the relevant cost of base materials. RTM and its variants (conventional, compression, and high-pressure) have been investigated by other authors [23, 24] who demonstrated that

compression RTM leads to a strong reduction of production costs and environmental impacts while maintaining good product performances.

Despite the abovementioned potentialities of PBM production processes, the scientific literature highlights a lack of quantitative analyses on the performances of such methods. In this context, this study aims to contribute to the state of the art by analyzing the PBM process from both economic and environmental points of view. An automotive part is considered as a reference case study to assess the process performance and compare it with the traditional autoclave processing. Different scenarios are considered in the analysis to include several combinations of processes (autoclave and PBM), molds (aluminum and composite), masters (polyurethane—Ureol and medium density fiberboard—MDF) and end of life (EoL) alternatives (landfill and incineration). Economic and environmental indicators are evaluated by considering different production scenarios in terms of available equipment and production volumes. More specifically, a parametric approach has been used to estimate production costs, while the environmental assessment has been conducted by using the well-known LCA methodology, as described in the ISO 14040-14044 standards. This study has been conducted in collaboration with an Italian company, leader in the production of CFRP components, mainly for the automotive sector. Outcomes of the present study can be used by manufacturing companies of the CFRP sector as a guide to select the most sustainable production technique, on the basis of the considered driver (environmental sustainability and/or production costs) and production volume.

The rest of the paper is organized as follows. After this Introduction, Section 2 describes the two analyzed manufacturing technologies. Section 3 illustrates the analysis methods used for the purpose of comparison. Section 4 describes the reference part, the goal and scope of the analysis, the system boundaries and the considered scenarios. Section 5 illustrates the full details about the inventory data. Section 6 reports the quantitative results obtained with the environmental and economic analyses. Section 7 critically discusses the outcomes of the study. Finally, Section 8 concludes the paper and proposes some directions for future research.

2 Manufacturing technologies

2.1 Autoclave processing

The autoclave processing, or vacuum bag process, is very common in all those markets where costs and production rate are not as important drivers as performances, such as aerospace or racing sector [8]. It is an open-molding process where the lay-up phase is conducted by skilled operators. This phase, especially in case of complex components (e.g., car frame),

requires long manufacturing time and it can be object of placement errors. To avoid this, researchers are focusing on developing automated lay-up systems which, however, require further improvements to demonstrate their effectiveness [25]. The raw material used in this kind of process is a prepreg that contains fibers in a B-staged epoxy resin.

The vacuum bag process can be divided in four main phases (Fig. 1): cutting, lay-up, molding, and de-molding. More in detail, during the cutting phase, the prepreg is taken from a refrigerator and it is kept at room temperature for defrosting. Then, it is laid on the cutting table to be cut in templates of desired shape, size, and orientation. Typically, prepreps are trimmed by means of a simple mat knife; however, laser beams, high-speed water jets, or trimming dies can be also used.

Backing paper is removed from the prepreg and the prepreg is laid down on the mold surface (lay-up phase). After the deposition of each prepreg ply, the entrapped air between layers is removed by means of a preliminary debulking operation. Once the designed stacking sequence is reached, the vacuum bag is created. Figure 2 shows in detail the schematic of a vacuum bag, highlighting the consumable materials typically used: release agent, release film, bleeder and/or breather, and vacuum bag. The release agent is employed to avoid adhesion in the mold surface on which the prepreg layers are laid up. The release film is a perforated film, applied on top of all the plies, to allow entrapped air, excess of resin, and volatiles to escape. The breather/bleeder is a porous fabric applied on top of the release film. The function of this layer is to absorb the excess of resin that flows out during the molding phase and to allow air and volatiles to escape from the laminate. The final layer is the vacuum bag that is generally a polyamide

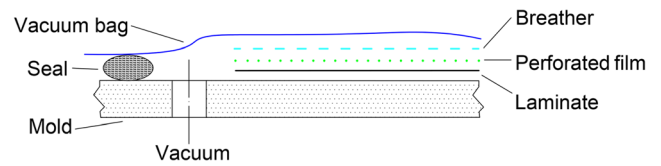
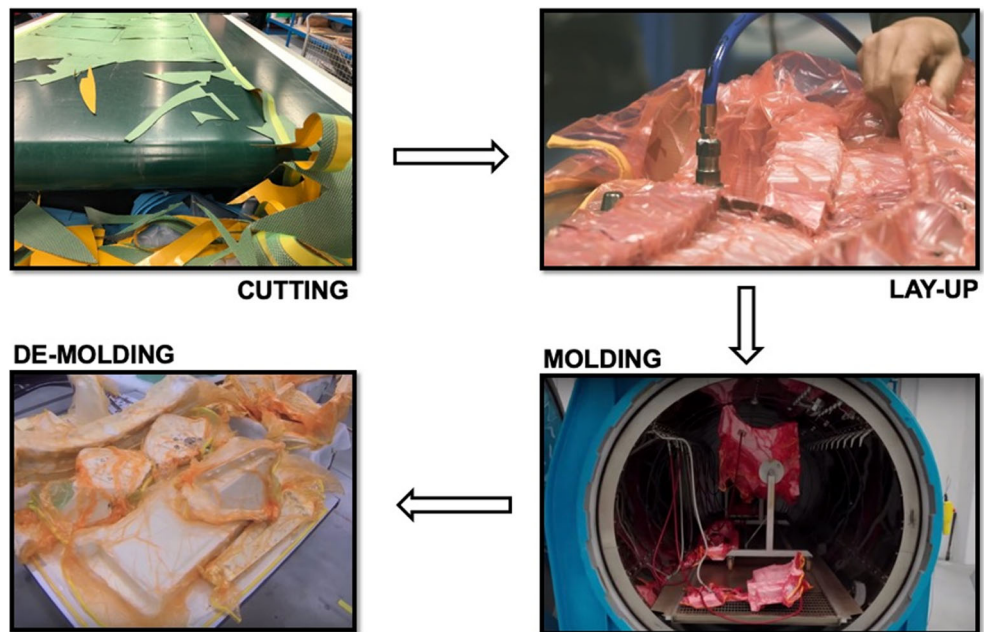


Fig. 2 Schematic of the vacuum bag process

(PA) film. After lamination and bagging, the entire assembly is placed inside an autoclave for curing and consolidation (curing phase). This process is reached out through the combination of external pressure, vacuum, and heat. The vacuum has the aim to eliminate air and volatiles while the external pressure to consolidate the laminate. The heat increases the velocity of the polymerization reaction until the complete cure of the matrix. The curing temperature and the pressure are maintained for 2 h or more, as function of the kind of resin and laminate, until the desired curing level is achieved. Once the curing process is completed, a cooling phase is needed for the de-molding of the part. The cooling occurs inside the autoclave using a dedicated cooling system. Then, the components are left outside the autoclave until they reach the room temperature.

The autoclave processing allows to have consistent material properties, high fiber volume, flexibility in fiber orientation, outstanding mechanical performances, and to produce complex shapes (rounded or with undercuts) without void or resin excesses. However, vacuum bagging presents also some limitations: it is a time intensive operation, especially for producing large components, and a lot of effort is necessary for an efficient seal of the bag (special tools may be used for detecting air leaks such as ultrasonic leak detecting device). Moreover, for the complete debulking of the uncured prepreg

Fig. 1 Main phases of the vacuum bag process



laminate, components are maintained under vacuum at room temperature for a very long time, depending from their geometry and dimensions [26]. For complex and high-performance components, the debulking phase can take more than 20 h [27]. The heating inside the autoclave is not efficient due to convective heat transfer process involved. Indeed, a large amount of gas needs to be heated for increasing the temperature of the components and of the relative molds. In addition, the airflow in the autoclave is not uniform and it is difficult to predict the exact time for the full polymerization avoiding extra time [28].

2.2 Pressure bag molding

The pressure bag molding (PBM) technique is similar to the well-known method called bladder molding [29] where an inflatable bladder (typically realized in latex) is used to produce hollow composite structures such as bike frames. The PBM exploits an inflatable counter-mold to replicate the compaction behavior proper of the autoclave, thus allowing the production of various-shaped components [30]. This counter-mold is typically made of silicon rubber and its thickness is appropriate to withstand pressure up to 10 bar [14]. The idea behind this process is to replicate the physical conditions that occur in the autoclave (e.g., hydrostatic pressure) avoiding the complications associated with the vacuum bagging and the typical long cycle time for the cure of the B-staged matrices.

Some similarities between the PBM and the autoclave process can be found. Indeed, also for this technique, the same four main phases can be identified (Fig. 3). Moreover, the cutting and the hand lay-up phases are analogous. However,

a less intensive and time-consuming debulking phase is typically required in case of PBM due to the higher compaction pressure which can be provided during the curing phase exploiting the inflatable counter-mold.

Considering the consumable materials necessary for this process, a perforated release film is placed over the prepreg preform and then a breather fabric is applied over this film to allow the escape of air and volatiles during the consolidation and to absorb resin excess coming from the stack of prepregs. Then, a plastic film is used between the breather and the counter-mold to avoid chemical attacks of the matrix to the silicone pressure bag. In Fig. 4, the scheme of the consumables used in case of PBM is reported.

The molding process is typically performed in a vertical press equipped with hot platens. This system allows to heat the prepreg stack at the curing temperature and to guarantee the counter-pressure necessary for maintaining the inflatable bag in the correct position.

The mold is typically realized in machined aluminum alloy and can present vents in different configurations for keeping the component under vacuum during the curing process. This metal mold allows to heat the laminate in an efficient way through conduction from hot platens. Moreover, by using virtual thermal simulations and dedicated heaters (such as cartridge heaters), it is possible to design the mold for obtaining uniform and rapid heating of the mold cavity [31]. In this way, a better monitoring of the curing process can be achieved, increasing the swiftness and the repeatability of the polymerization process.

Other potential advantages come from the cooling and demolding phases. In the PBM process, the cooling can be faster with respect to the autoclave process thanks to the use of

Fig. 3 The main phases of the PBM process

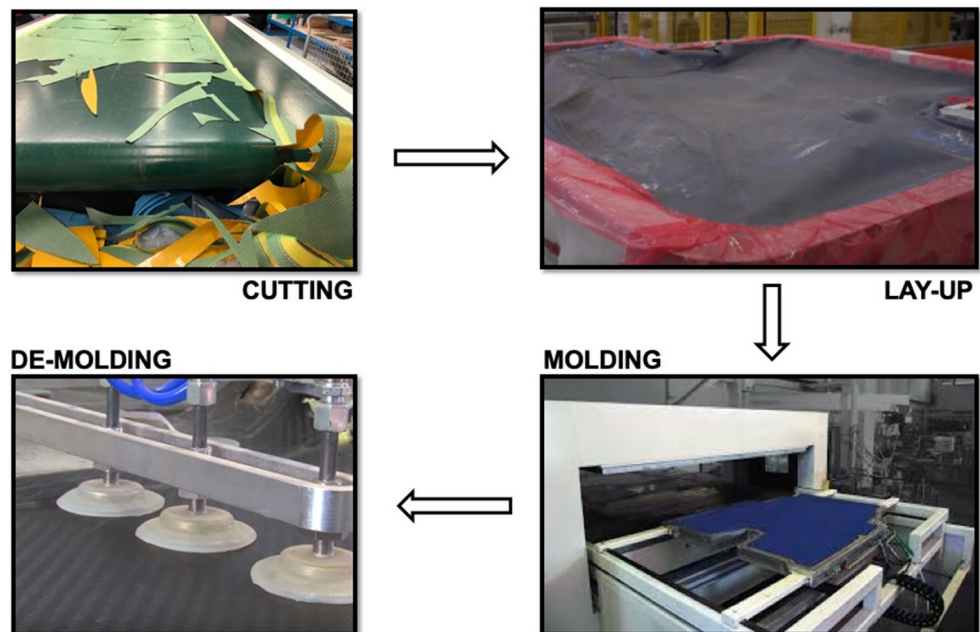
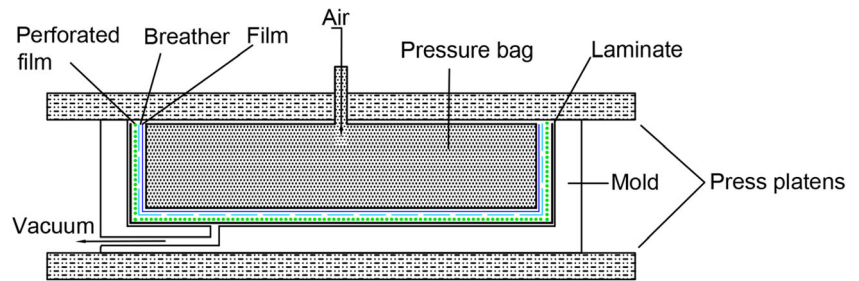


Fig. 4 Materials, tools, and consumables required for the PBM process



optimized cooling systems. For example, cooling channels which exploit thermal fluids (e.g., ethylene glycol) can be provided inside the mold to remove heat efficiently. Indeed, the same fluid used as cooler can be directed to another mold for the pre-heating process.

3 Methods

Two different analysis methodologies have been used to estimate and compare the economic and environmental impacts of the two considered CFRP manufacturing processes. The next sub-sections introduce the life cycle assessment methodology (section 3.1), used to assess the environmental impacts, and the parametric approach (section 3.2), used to estimate the production costs of the different process alternatives.

3.1 Life cycle assessment

Life cycle assessment is a framework for assessing the environmental impact related to products, processes, and services activities throughout their whole life cycle (i.e., from cradle to grave). The method is standardized according to the ISO 14040-14044 [32, 33], which define respectively the framework and the guidelines for implementation.

LCA is a systematic tool which could support the decision-making process for new product and process design and guide the optimization of energy and resource consumption in a life cycle perspective. According to the standardized methodology, four different phases must be completed:

1. Goal and scope definition: during this phase, the objectives of the analysis need to be clarified, the considered functional unit must be univocally defined, and the spatial and temporal system boundaries must be identified;
2. Life cycle inventory: this is a key phase of an LCA study in which the system under analysis is subdivided in elementary steps. Successively, for each identified step, an input-output analysis is conducted to collect and classify all the relevant flows;
3. Life cycle impact assessment: during this phase, the input-output flows are translated in midpoint and/or endpoint impact categories through the application of an impact

assessment methodology, based on characterization and/or weighting factors;

4. Results interpretation: the last phase foresees the analysis, interpretation, and critical review of the obtained results, as well as the definition of possible improvement strategies.

Among the different available LCA software tools, the SimaPro 8.0.5.13 has been used to carry out the present study. This tool integrates the Ecoinvent 3.1 database [34] used as source of secondary inventory data.

3.2 Cost analysis

A cost estimation analysis for the comparison of the different scenarios has been carried out through a largely used parametric approach. This method involves the segmentation of a process into unitary activities and the use of specific formulas perceived as black boxes that combine parameters to estimate costs for each unitary activity [35]. The parameters taken into account in the present study are raw materials, consumables, labor, energy, and equipment. In this cost model, only direct costs are considered which means that overheads, maintenance, and machine amortizations do not contribute to the determination of the final cost. The component production cost can be calculated as sum of costs of each unitary activity by considering the production volume for the allocation of equipment and tools. Finally, a breakdown of the cost can be drawn to evaluate the contribution of each activity (e.g., cost of a single manufacturing step) and production parameter (e.g., cost related to the consumption of electric energy, cost of labor). Input data are typically derived from industrial sources and purchases made directly.

4 Goal, scope, and system boundaries

4.1 Description of the analyzed part

The component studied in this research is a CFRP rear diffuser of a luxury car. Since the manufacturing steps needed to realize this part are the standard ones needed to produce every non-structural automotive CFRP part, this component can be

considered representative for the purpose of comparing two different manufacturing techniques. The considered rear diffuser is made of high-strength carbon fiber fabric and epoxy resin. In addition, a polyurethane foam is used as core in the parts where higher stiffness is required. The latter weighs around 0.3 kg. The stacking sequence and the detail of the materials used cannot be reported due to confidentiality reasons. The final weight is around 8 kg, while the surface is around 3 m². The total perimeter of the prepreg cutting templates, realized using a computer numerical controlled (CNC) cutting machine, is around 13 m.

4.2 Goal, functional unit, and scenario description

The goal of this study is to quantify and compare the environmental and economic performances of the two different processes for CFRP component manufacturing described in Section 2: standard autoclave processing and pressure bag molding.

The functional unit has been defined as the production of the part previously described in section 4.1 (i.e., rear diffuser of a luxury car). The following eight different scenarios have been considered to simulate different realistic cases:

- *Scenario 1.1*: autoclave processing with aluminum mold and landfill as EoL scenario for all the non-recyclable materials;
- *Scenario 1.2*: autoclave processing with aluminum mold and incineration as EoL scenario for all the non-recyclable materials, except those ones that are not incinerable;
- *Scenario 2.1*: autoclave processing with composite mold, plastic master, and landfill as EoL scenario for all the non-recyclable materials;
- *Scenario 2.2*: autoclave processing with composite mold, plastic master, and incineration as EoL scenario for all the non-recyclable materials, except those ones that are not incinerable;
- *Scenario 3.1*: autoclave processing with composite mold, medium density fiberboard master, and landfill as EoL scenario for all the non-recyclable materials;
- *Scenario 3.2*: autoclave processing with composite mold, medium density fiberboard master, and incineration as EoL scenario for all the non-recyclable materials, except those ones that are not incinerable;
- *Scenario 4.1*: PBM processing with aluminum mold and landfill as EoL scenario for all the non-recyclable materials;
- *Scenario 4.2*: PBM processing with aluminum mold and incineration as EoL scenario for all the non-recyclable materials, except those ones that are not incinerable.

In addition, different production volumes (from a minimum of 25 pieces to a maximum of 3250 pieces) have been

simulated to analyze the influence of process variables (e.g., molds, masters, workers) on costs and environmental impacts.

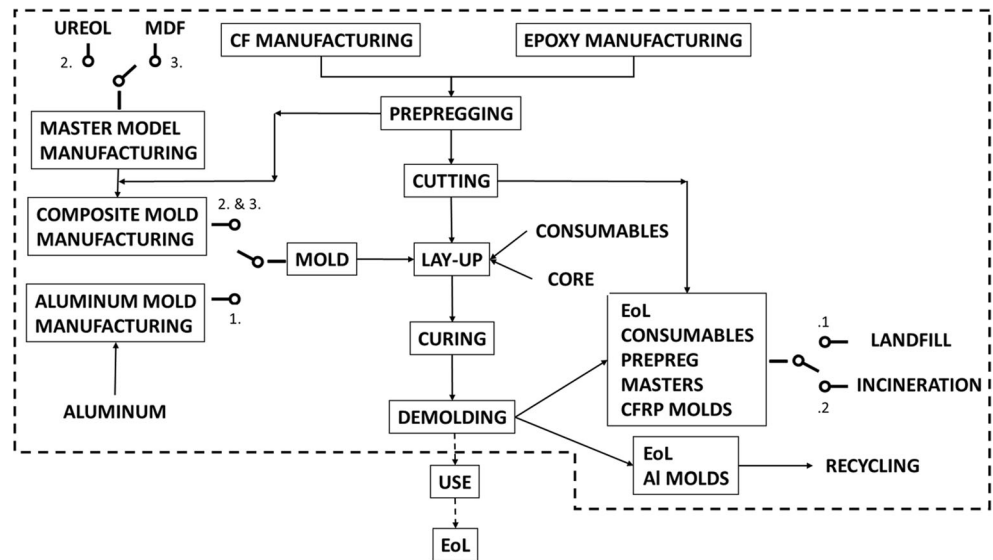
4.3 System boundaries

In this study, the life cycle assessment is carried out considering three phases: raw materials, manufacturing, and end-of-life. The first phase concerns the extraction of the raw materials and the production of both CF and epoxy resin, considering also the prepregging operation. The manufacturing of consumable materials used in each process is also considered as well as their disposal, assumed to be through incineration with energy recovery or landfilling. The EoL is only considered for aluminum molds (recycling) and for consumables, CFRP molds, counter-molds, and masters (incineration or landfilling). The use and the disposal phases of the analyzed CFRP rear diffuser are not taken into account due to the fact that they produce similar impacts both for vacuum bag and PBM processes. Moreover, the uncertainty in the recycling method and the long lifespan of the part can lead to an incorrect evaluation of the impacts associated to the EoL of the component.

The investigated scenarios for the vacuum bag process (six different alternatives) are reported in Fig. 5. The carbon fibers are realized starting from the polyacrylonitrile precursor and then prepregged with the epoxy resin through a hot melt process. Then, the cutting machine realizes the templates used in the lay-up process, producing scraps of prepreg and of backing paper (polyethylene terephthalate—PET). In the lay-up phase, aluminum or CFRP molds can be used. The latter can be realized starting from a polyurethane (commonly called Ureol) or MDF master model. In this phase, core material is added to the prepreg for realizing a sandwich panel and consumables such as release film, breather, and vacuum bag are used. Then, the curing occurs in an autoclave following the prescribed curing cycle. After that, the component is demolded and, in accordance with the respective lifespan, the molds can be reused, recycled (Al molds), or disposed (CFRP molds). The dotted line in Fig. 5 represents the system boundary, highlighting that the use and EoL phases of the analyzed part are not considered.

Similarly, Fig. 6 reports the scenarios (two alternatives) related to the PBM process. The raw materials phase is equal to that of the vacuum bag process as well as the cutting phase. The difference concerns the lay-up phase where less consumables are used and where a silicone counter-mold is produced. The curing phase occurs in a press heated by hot platens and the de-molding takes into account also the chilling operation to reduce the temperature of the molds. Also in this case, two EoL alternatives (incineration and landfilling) are considered for consumables, prepreg scraps, and counter-molds. The aluminum molds, after their useful life, are considered recyclable. The use and EoL phases of the produced component are not

Fig. 5 System boundaries of the scenarios 1.1–3.2



included in the system boundaries, as in the case of the vacuum bag process.

5 Inventory data

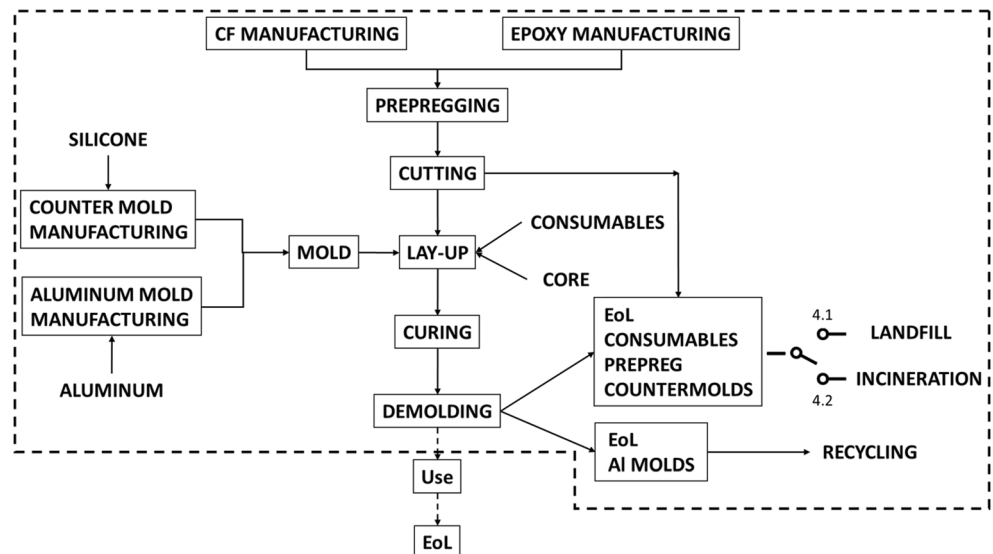
Since the manufacturing of CFRP and carbon fibers are not currently modeled in the Ecoinvent and in any other commercial Life Cycle Inventory (LCI) database (GaBi planned to release an LCI database for carbon composites during 2019), data from relevant literature studies have been considered to build a as reliable as possible model for the prepreg manufacture. In particular, the inventory for the production of the precursor, i.e., polyacrylonitrile (PAN), is based on the study of Duflou et al. [5] who detailed the polymerization process of the acrylonitrile (AN) basic monomer that involves the use of electric energy, steam, and a solvent. The successive step

consists in the production of carbon fibers, whose process has been modeled according to the inventory reported by Khalil [36]. This study reports one of the most recent and updated inventories for carbon fibers production. Finally, according to the technical data sheet of the analyzed material, the prepreg has been modeled by considering a content of carbon fibers and epoxy resin of 64% and 36% (in weight), respectively. The prepregging process has been modeled on the basis of literature data derived from Song et al. [20].

Concerning the cutting phase, the electric energy consumption has been measured directly from the cutting machine (Nominal power 7 kW), using the PQA824 power analyzer by HT Instruments.

The quantities of materials needed, as well as the scraps generated, during the manufacturing of masters and molds have been calculated on the basis of the available 3D models. The CFRP molds used in scenarios 2.1, 2.2, 3.1, and 3.2 has

Fig. 6 System boundaries of the scenarios 4.1 and 4.2



been modeled as a standard CFRP part realized with the autoclave process (from PAN production to de-molding).

Regarding consumables, the quantities and materials typologies have been derived by weighing each item and/or consulting their data sheets.

The electric energy consumptions for the different phases of the PBM process have been measured through the aforementioned power analyzer. Again, with regard the PBM process, the compressed air needed during the inflation has been calculated on the basis of the inflatable counter-mold volume. The electric energy consumed during the curing phase in the autoclave process, instead, has been estimated on the basis of literature data [20].

As explained in section 4.3, the EoL of the analyzed part (after its useful life) is out of scope of the present study, while the EoL of scraps generated during the processes and consumables has been considered. To model the landfill and incineration treatments, secondary data have been used. Concerning the aluminum molds (both in case of autoclave and PBM scenarios), the EoL has been modeled by considering a recycling scenario. Considering that the molds have a monolithic structure composed by a single material, thus they are very easy to recycle; the recycling rate has been set to 80%, a slightly higher value than the standard rate (about 70%) of the aluminum recycling chain in developed countries [37].

Table 1 summarizes the full details of the inventory data about the material and energy flows for the eight analyzed scenarios.

The Ecoinvent 3.1 system model “allocation, default” version has been used as source of secondary LCI data [34].

Concerning the cost analysis, secondary cost data have been assumed on the basis of historical data provided by the involved company (Table 2). The autoclave and the PBM processes also differ for the processing time. In the vacuum bag process, the hand lay-up phase, considering also compaction and debulking phases, lasts 360 min. Then, for the curing cycle and for the chilling in the autoclave, 240 min is required for a total of 600 min. Differently, the hand lay-up of the PBM requires less time due to a faster debulking and compaction phases. In particular, the lay-up lasts 240 min. In addition, the curing cycle is faster in the press due to a more efficient heating based on metal conduction instead of air convection, resulting in a curing time of 105 min. However, a chilling station is required to decrease the temperature of the mold, accounting for 60 min. The total cycle time for the PBM is 405 min.

Since the goal of the present study also includes the simulation of different production volumes, the calculation of the needed equipment has been carried out. The following hypotheses have been considered:

- The modeling considers endless equipment and human resources, i.e., the number of PBM lines, autoclaves,

masters, molds, counter-molds, and operators increases with the production volume. In this way, it is always possible to start the production of a new piece and the waiting time between the different phases is always null;

- The autoclaves are assumed to work in full load condition;
- According to the indications provided by the involved company, the following durations of the useful life before replacement have been assumed: (i) CFRP molds: production of 99 pieces, (ii) aluminum molds: 999 pieces, (iii) counter-molds: 99 pieces, and (iv) masters: 5 pieces.

The simulation includes all the production volumes from 250 pieces per year to 3250 pieces per year with a step of 250. In addition, a more detailed simulation has been carried out for low production volumes, by considering a step of 25 in the range 25–250 pieces. As explained in the next sections, this was necessary for the purpose of identifying the breakeven points among the different alternative technologies in the cost analysis. Table 3 reports the number of masters, molds, and counter-molds needed for each production volume of each scenario. As can be seen comparing the scenarios 1 and 4, the number of aluminum molds required for high production rate is different. This is due to the fact that cycle time in the autoclave process is higher than in the PBM, resulting in a higher number of molds necessary to guarantee the same production rate.

6 Results

6.1 Life-cycle assessment

A large variety of environmental impact assessment methods (e.g., CML, ILCD Midpoint) and indicators (e.g., climate change, ozone depletion potential) can be used to quantify the life cycle environmental impacts of any product or process. In this study, the ReCiPe 2008 LCIA methodology has been used [38] to take into account the different typologies of impacts (e.g., depletion of fossil resources, human toxicity) and to have a comprehensive view on the potential environmental damages. This methodology allows to derive results at both midpoint (18 impact categories) and endpoint (3 damage categories successively grouped in 1 single score) levels. In particular, results are presented in terms of the following indicators: (i) Climate change midpoint category (measured in [kg CO₂ eq]), calculated according to the impact assessment method described in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) [39], and (ii) ReCiPe Endpoint (H)—Europe H/H single score (measured in [EcoPt]), calculated by considering the Hierarchist (H) perspective weighting sets at midpoint and endpoint levels, as well as the normalization factor relative to a European citizen in the year 2000. These environmental

Table 1 Inventory data for material and energy flows

		Scenario			
		1.1 and 1.2	2.1 and 2.2	3.1 and 3.2	4.1 and 4.2
Input material	Carbon fiber (prepreg)	6.4 kg	6.4 kg	6.4 kg	6.4 kg
	Epoxy resin (prepreg)	3.6 kg	3.6 kg	3.6 kg	3.6 kg
	PU (core)	0.3 kg	0.3 kg	0.3 kg	0.3 kg
Cutting	Electric energy	0.082 kWh	0.082 kWh	0.082 kWh	0.082 kWh
	Prepreg scrap	2 kg	2 kg	2 kg	2 kg
Master	Polyurethane	–	182 kg	–	–
	MDF	–	–	0.2 m ³	–
Mold	Aluminum	67 kg	–	–	437 kg
	Aluminum scrap	41 kg	–	–	268 kg
	CFRP	–	15 kg	15 kg	–
Counter-mold	Silicone rubber	–	–	–	15 kg
	Electric energy (curing)	0.5 kWh	0.5 kWh	0.5 kWh	0.5 kWh
Lay-up	PA66 (vacuum bag)	0.5 kg	0.5 kg	0.5 kg	–
	TFE (film)	–	–	–	0.097 kg
	PET (breather)	0.375 kg	0.375 kg	0.375 kg	0.25 kg
	TFE (release film)	0.055 kg	0.055 kg	0.055 kg	0.055 kg
	Organic solvent (release agent)	0.03 kg	0.03 kg	0.03 kg	0.03 kg
Curing	Electric energy (curing autoclave)	11 kWh	11 kWh	11 kWh	–
	Electric energy (heating)	–	–	–	46.1 kWh
	Electric energy (clamp)	–	–	–	3.9 kWh
	Compressed air at 6 bar (inflation)	–	–	–	0.61 m ³
De-molding	Electric energy (chilling)	–	–	–	16 kWh

metrics can be considered the most representative for the specific application, as demonstrated in other literature studies focused on the environmental assessment of CFRP components, production processes, or end of life [6, 18, 21, 36].

Table 2 Secondary cost data

Item	Cost
Prepreg	80 €/kg
Polyurethane master	6.000 €/piece
MDF master	800 €/piece
Aluminum mold (autoclave)	5.000 €/piece
CFRP mold (autoclave)	1.900 €/piece
Aluminum mold (PBM)	20.000 €/piece
Counter-mold	700 €/piece
Core	70 €/kg
Release film	0,9 €/m ²
Release agent	60 €/l
Vacuum bag	0,8 €/m ²
Breather	3,75 €/m ²
Film	1,9 €/m ²
Electric energy	0,2 €/kWh
Labor	20 €/h

Figure 7 and Fig. 8 report the total environmental impacts calculated for each manufacturing process and for each scenario, considering the climate change and ReCiPe single score indicators, respectively. Analyzing the graphs, it is clear that regardless the chosen indicator and the production volume, the curves have similar trends: autoclave process (scenarios 1.1–3.2) has lower impacts than the PBM process (scenarios 4.1 and 4.2). In addition, the difference among the two CFRP manufacturing process families in terms of environmental load increases linearly with the production volume. The most environmentally friendly solution is always represented by the autoclave process with aluminum molds.

Comparing the three typologies of autoclave processes (i.e., aluminum mold, CFRP mold with polyurethane master, CFRP mold with MDF master), the impacts are analogous and differ at maximum of about 4% considering the climate change indicator at the highest production volume (in case of ReCiPe single score the differences are even minor).

Another interesting result is related to the considered EoL scenarios. The LCA results show that the influence of the chosen EoL scenario in the total environmental impacts is very low. For all the considered manufacturing process variants and for both the indicators, the differences among the

Table 3 Analyzed production volumes and relative needed molds, counter-molds, and masters for each scenario

Production volume [N° pieces]	Scenarios 1.1 and 1.2		Scenarios 2.1 and 2.2 and 3.1 and 3.2		Scenarios 4.1 and 4.2	
	Molds [N°]	Molds [N°]	Masters [N°]	Molds [N°]	Counter-molds [N°]	
	25	1	1	1	1	1
50	1	1	1	1	1	
75	1	1	1	1	1	
100	1	2	1	1	2	
125	1	2	1	1	2	
150	1	2	1	1	2	
175	1	2	1	1	2	
200	1	3	1	1	3	
225	1	3	1	1	3	
250	1	3	1	1	3	
500	1	6	2	1	6	
750	2	8	2	1	8	
1000	2	11	3	2	11	
1250	3	13	3	2	13	
1500	3	16	4	2	16	
1750	4	18	4	2	18	
2000	4	21	5	3	21	
2250	5	23	5	3	23	
2500	5	26	6	3	26	
2750	6	28	6	3	28	
3000	6	31	7	4	31	
3250	7	33	7	4	33	

landfill and incineration EoL scenarios are almost negligible (a maximum deviation of 2.3% is observed).

To better understand why the PBM is the less sustainable process, the split of the different contributions in terms of

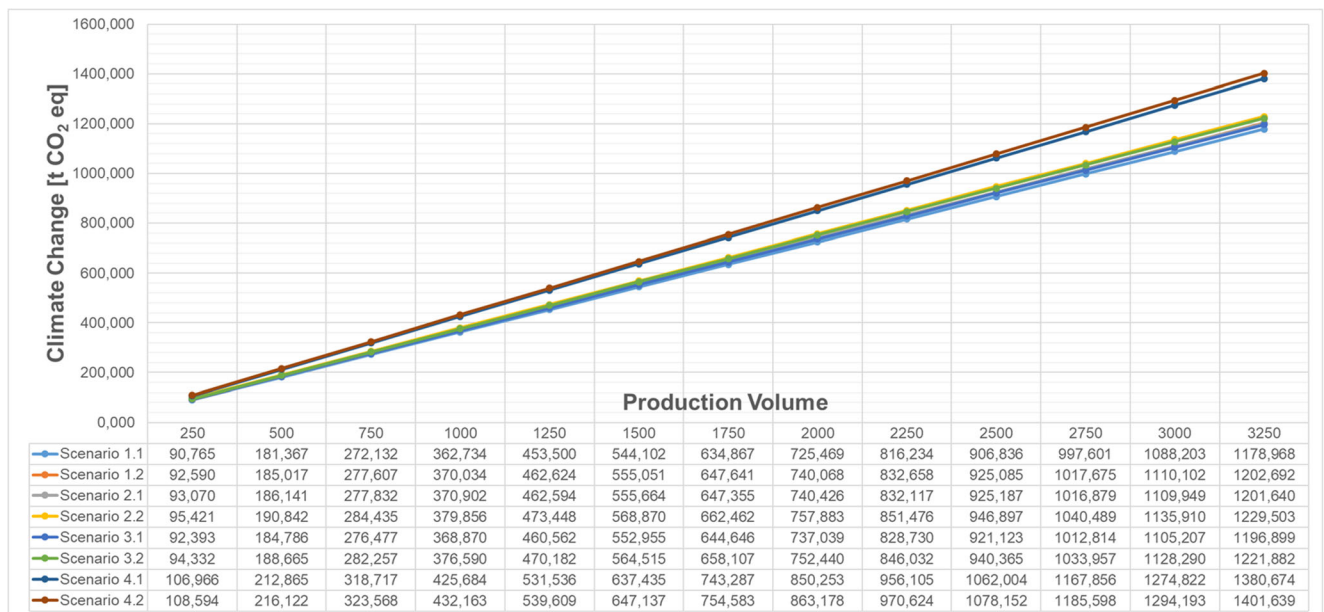


Fig. 7 Climate change vs production volume for the different manufacturing processes and scenarios

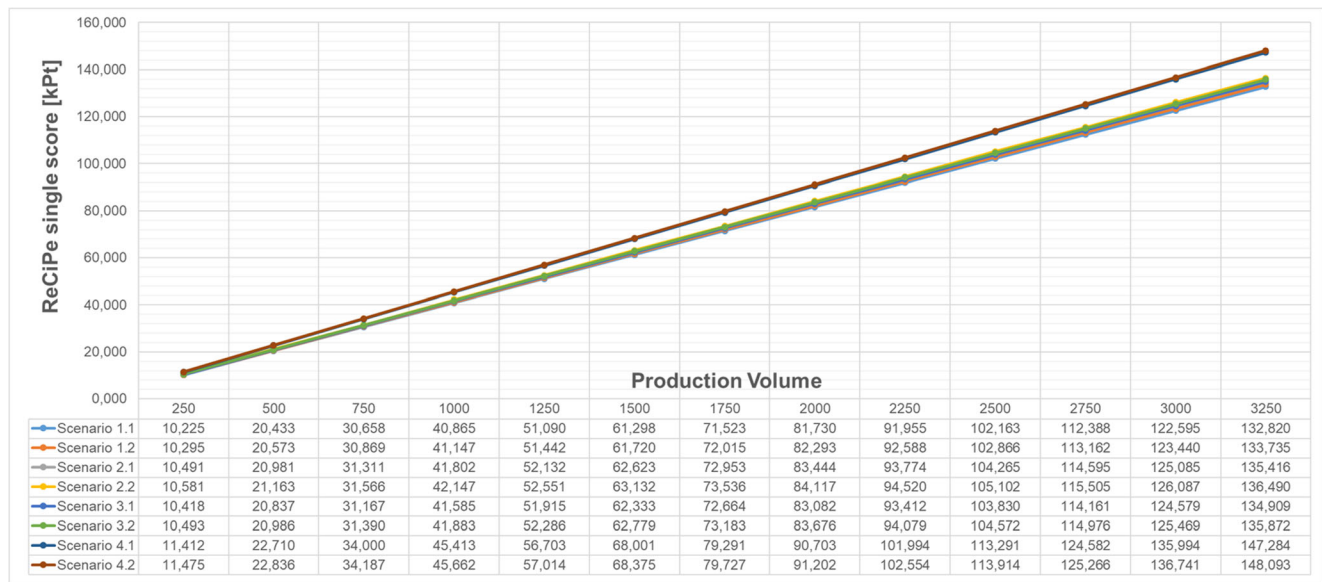


Fig. 8 ReCiPe single score vs production volume for the different manufacturing processes and scenarios

ReCiPe single score has been carried out (similar results can be obtained for the climate change indicator). Considering that the EoL phase causes negligible impacts/benefits, only the landfill has been considered. Analyzing the impact breakdown for the four alternative processes (Fig. 9), it is clear that most of the impacts (more than 90% of the total) are due to the input material that represents a fixed contribution for all the scenarios. The higher environmental impacts of the PBM (scenario 4.1) are caused by three main reasons:

- The higher contribution from consumables: in the case of PBM, silicone rubber inflatable counter-molds need to be used. The high weight of this consumable (15 kg as reported in the inventory, Table 1) causes a relevant contribution to the total environmental impacts;
- The higher contribution of the curing and de-molding (particularly cooling) phases: in the case of PBM, more massive molds need to be used in order to guarantee a sufficient compression strength (as reported in Table 1, PBM aluminum molds weigh 437 kg, while autoclave aluminum molds weigh only 67 kg). As a consequence, the thermal inertia of molds is much higher than in case of autoclave and the needed energy to heat up and cool molds is very high, causing relevant environmental impacts.

Considering the three alternative autoclave processes (scenarios 1.1 and 2.1 and 3.1), the differences are due to molds. The higher service life of the aluminum mold leads to less environmental impacts than in case of CFRP molds; therefore, the scenario 1.1 can be considered the most sustainable one. Finally, the deviations among scenarios 2.1 and 3.1 are due to

the master production and disposal: the MDF master is more environmentally friendly than the Ureol master.

6.2 Cost analysis

In this section, the results of the cost analysis are reported. The study has been conducted using the inventory data reported above.

In Fig. 10, the total cost of the different manufacturing processes is reported as a function of the production volume. As can be seen, the autoclave scenarios show comparable results, while the PBM presents significantly lower values.

The cost breakdown of the autoclave with plastic master (used as a reference) and of the PBM processes is reported in Fig. 11, where the cost items are also highlighted. In addition to the costs related to raw materials needed for the manufacturing of the product (pregreg, breather, films, etc.), the “material cost” item includes also all the costs related to the manufacturing process (cutting, curing, etc.). The “labor cost” instead is related only to the manual lay-up of the product. The cost of the CFRP molds (raw materials, lay-up, and manufacturing) is charged in the “mold cost” item, as well as the cost of the aluminum molds for the PBM. The cost for the realization of the master models is reported in the “master model cost” item. It is worth noticing that in the autoclave process, the majority of the cost can be attributed to the labor cost, followed by the material cost. The cost of the CFRP molds and of the master models is negligible and, for this reason, the breakdown of the processes with aluminum and MDF molds is not reported. For the PBM process, the item “counter-mold cost” takes into consideration the cost of the silicone, the labor and the cost of the curing process.

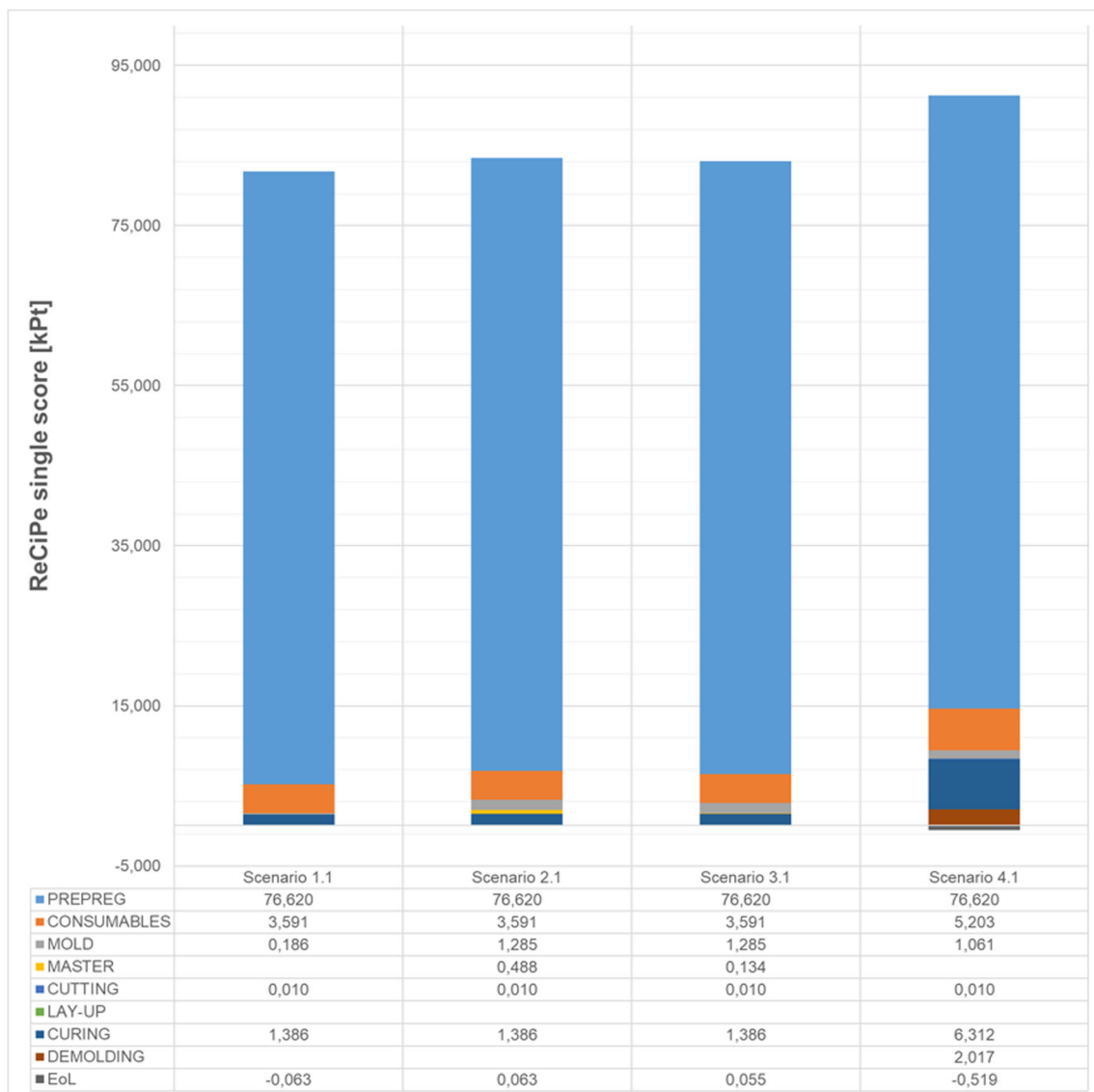


Fig. 9 Split of contributions for a production volume of 2000 pieces in terms of ReCiPe single score

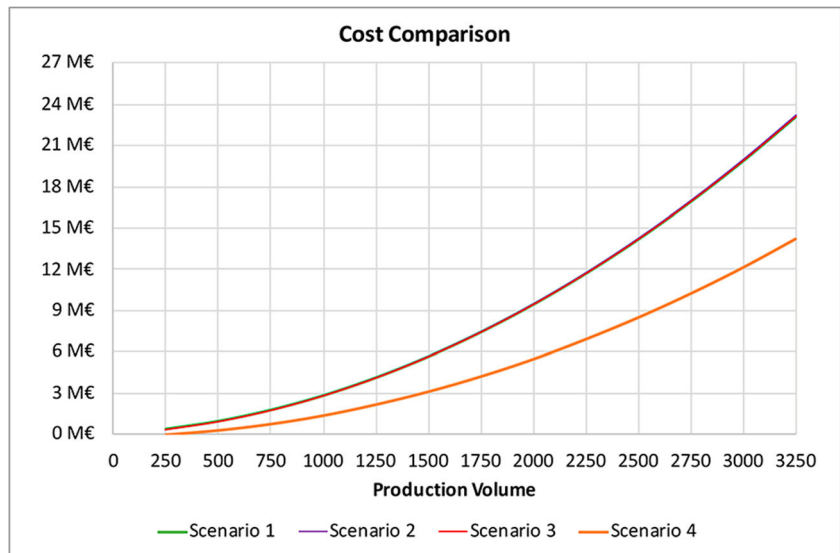
7 Discussion

Results presented in Section 6 highlight that an optimum solution of CFRP manufacturing process from both the environmental and economic points of view cannot be found. If the autoclave processes are the most environmentally friendly alternatives (in particular the autoclave with aluminum mold), from the economic point of view the situation is completely reversed. Indeed, Fig. 10 shows that the PBM process is economically convenient with respect to autoclave processes, especially at high production rates. Analyzing the breakdown of the cost items (Fig. 11), this outcome can be attributed to the lower manufacturing time required for the lay-up phase. In the PBM process, the manual lay-up (considering also the debulking phase) requires 2 h less than in the autoclave, allowing, with the same workforce and thus with the same labor cost, a higher production rate. Another relevant aspect

is that, except the labor and material costs, the other items lead to very low contributions at high production rates. Indeed, the cost relative to molds, to master models and to counter-molds can be considered negligible at production rates higher than 250 units.

Since for both the analyses the gap among the different process alternatives tends to decrease by reducing the production volume, a detailed analysis at low production volumes has been done. In particular, the behavior of the environmental impact and cost trend has been calculated for production volumes in the range 25–250 units (step 25). The aim of this specific analysis was to identify breakeven points (in terms of number of pieces to produce) that separate the areas for which the autoclave processes are convenient from the area for which the PBM process is convenient. The result of this activity is reported in Fig. 12, and also in this case, different outcomes can be observed among the environmental and cost impacts.

Fig. 10 Total cost vs production volume for the different manufacturing processes and scenarios



Concerning the environmental indicators (Fig. 12a and Fig. 12b), no breakeven points can be identified since the PBM curve remains above the autoclave curves for each production volume. Independently from the number of pieces produced, PBM does never represent the most environmentally friendly process for the production of automotive CFRP components.

The cost analysis (Fig. 12c), instead, provides a different outcome and several breakeven points have been identified. As can be seen, at very low production rates (less than

107 units), the autoclave processes are cheaper than the PBM, mainly due to the higher cost of the mold in the latter process which represents the 40% of the total manufacturing cost (at 25 units produced). Increasing the production volume to a value higher than 107 units, the autoclave process with CFRP mold and polyurethane master model becomes more expensive than the PBM, confirming that the major contribution is related to the labor cost of the lay-up phase which account for more than 30% of the total. Then, at a value of 137 units produced, the autoclave process based on CFRP

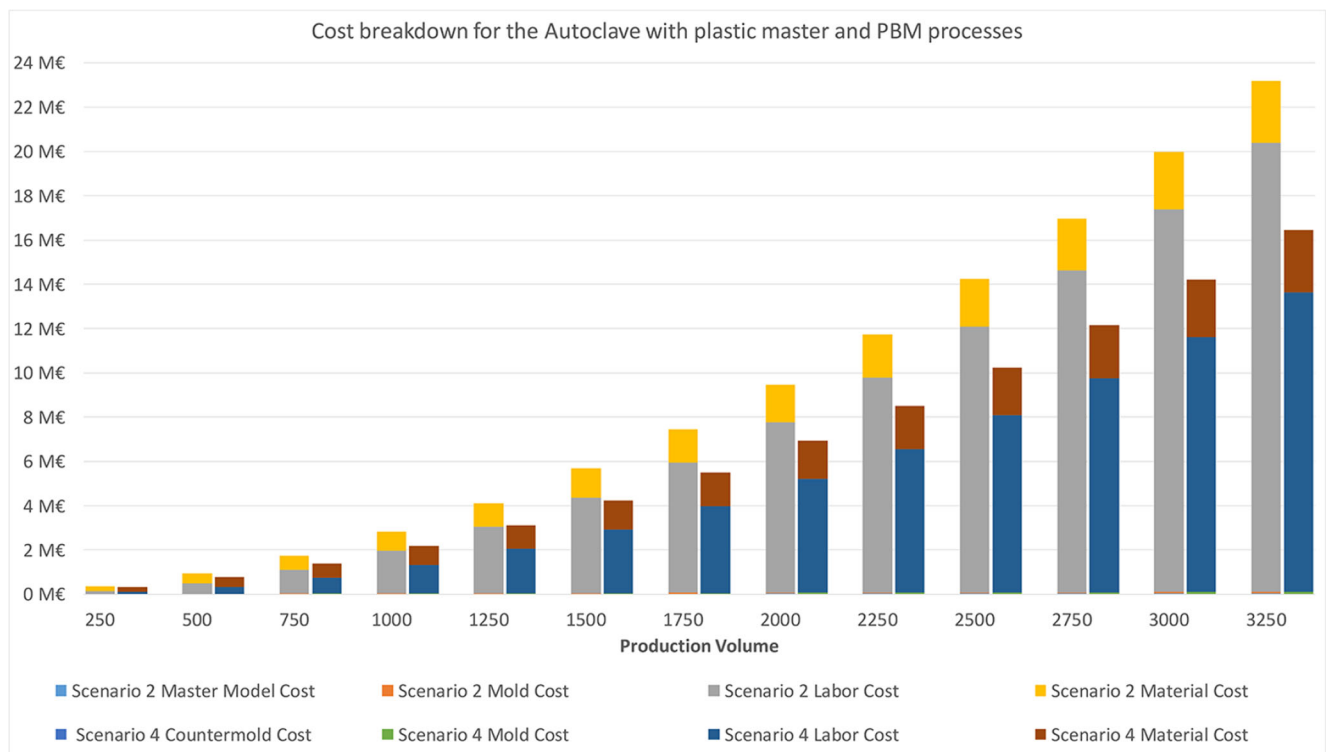
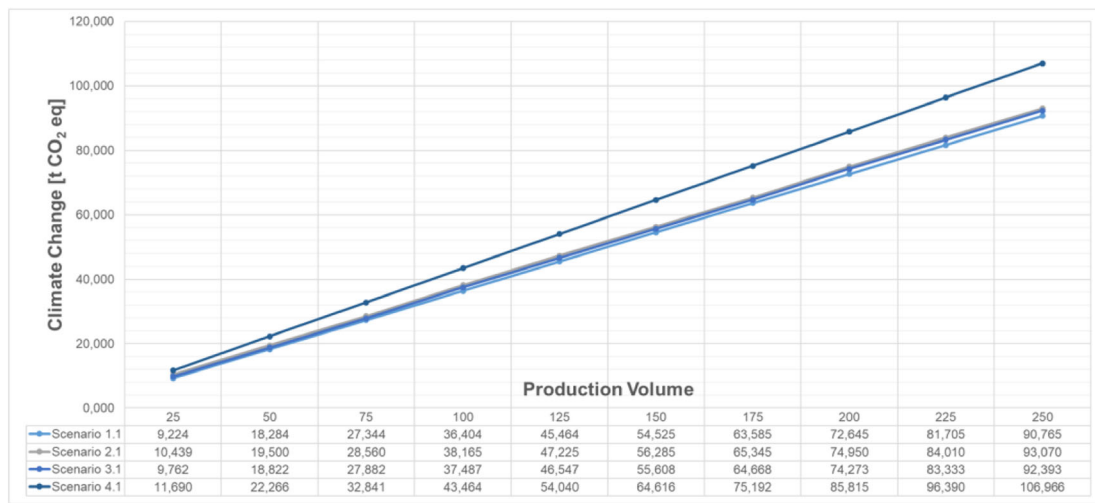
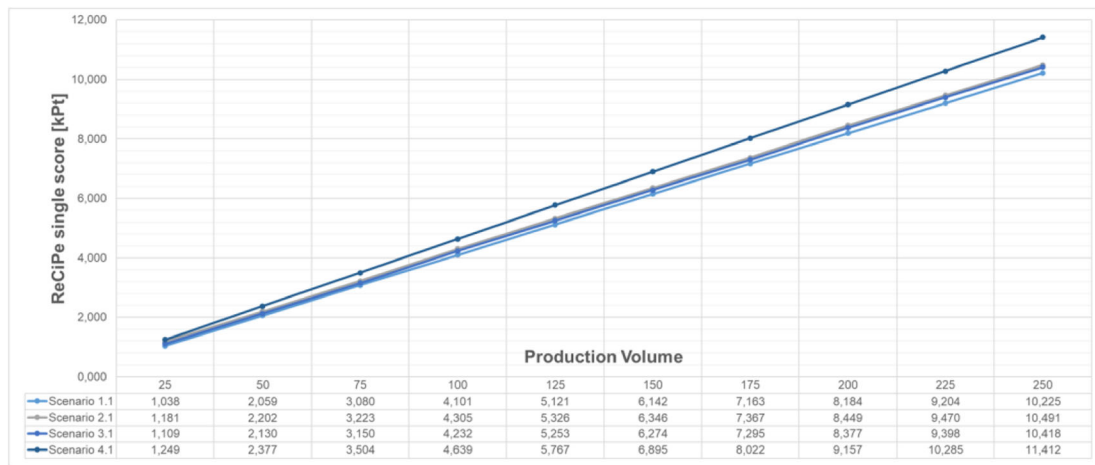


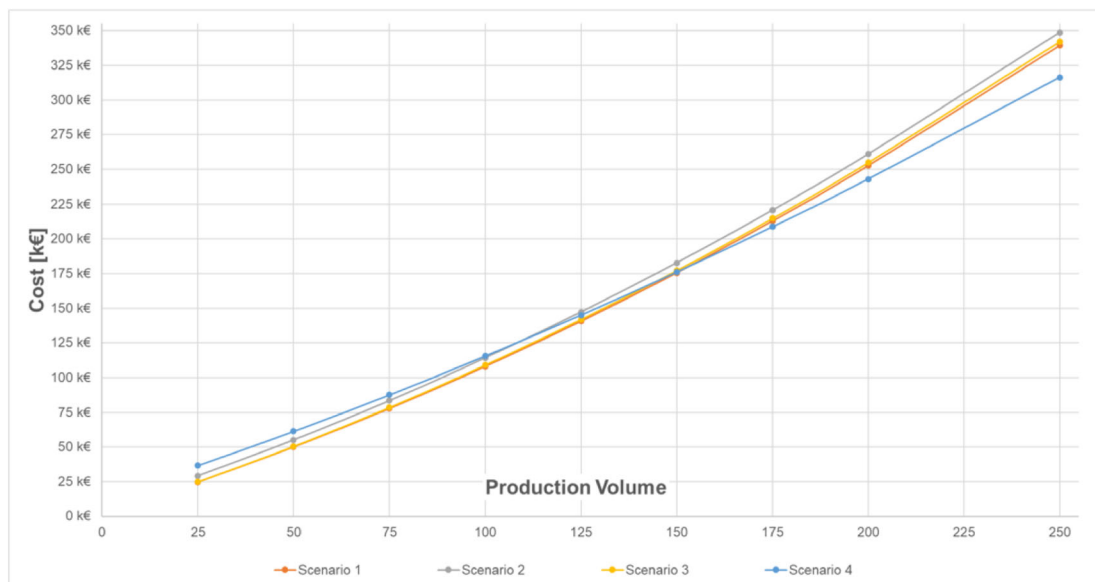
Fig. 11 Cost breakdown for the autoclave process with CFRP mold and polyurethane master and for the PBM process



a



b



c

Fig. 12 Environmental analysis at low production volumes for climate change (a), ReCiPe single score (b), and cost indicators (c)

molds and MDF models demonstrates higher costs than the PBM. Finally, the breakeven point for the autoclave process with aluminum molds can be calculated at 140 units. After this value, the PBM process becomes the most economically sustainable option for producing CFRP components.

8 Conclusions

In this study, a comparative analysis of the environmental and economic performances of the standard autoclave and pressure bag molding processes has been conducted. In addition, various scenarios based on different production rates, mold manufacturing techniques, and EoL alternatives have been evaluated. From an environmental point of view, results show that the autoclave process leads always to less environmental impacts than the PBM process. This result is valid for a production volume which range from 25 to 3250 units with a divergent trend between the two processes. In addition, no significant differences can be found if composite or aluminum molds are used in the vacuum bag process as well as the contribution of the EoL can be considered negligible. Differently, from the economic point of view, results demonstrate that the more the production volume is, the more convenient the PBM process becomes. However, different breakeven points have been found at low production rates where the PBM is more expensive due to the higher costs of the mold. Autoclave process might become economically favorable if the lay-up and curing phases were optimized, using for example automatic deposition methods or fast curing resins. On the other hand, the PBM process could be greener if efforts will be focused on the reduction of the impacts related to the heating and cooling phases that now account for most of the process impacts.

In conclusion, since the result is not influenced by the quantity of raw materials used, it can be considered valid for all the composite components similar to the one here presented. Thus, this analysis can represent a useful decision-making tool for manufacturing engineers in choosing the best CFRP production process from the economic and environmental points of view.

Future work will be focused on the investigation of other manufacturing processes in order to conduct more comprehensive comparative analyses between these methods, and thus facilitating the decision-making process of the technologists. Furthermore, more detailed and reliable environmental assessments will be conducted taking into account also the transportation and moving forward primary data instead of literature and LCI database information. Finally, later stages of the CFRP part life cycle (e.g., use of the CFRP rear diffuser, EoL of the CFRP part) could be considered in future research activities in order to have a more comprehensive view on the

impacts and benefits related to the use of composite parts in the automotive sector.

Acknowledgments The authors acknowledge the support offered by HP Composites s.r.l. (Ascoli Piceno, Italy) for the data retrieval.

References

- Holmes M (2017) Carbon composites continue to find new markets. *Reinf Plast* 61:36–40. <https://doi.org/10.1016/j.repl.2016.12.060>
- Mathes V (2018) The composites industry: plenty of opportunities in heterogeneous market. *Reinf Plast* 62:44–51. <https://doi.org/10.1016/J.REPL.2017.05.002>
- Rao S, Simha TGA, Rao KP, Ravikumar GV V. (2015) Carbon composites are becoming competitive and cost effective. *Infosys website* 2–3
- Nickels L (2017) Composites driving the auto industry. *Reinf Plast* 62:38–39. <https://doi.org/10.1016/j.repl.2017.11.013>
- Duflou JR, De Moor J, Verpoest I, Dewulf W (2009) Environmental impact analysis of composite use in car manufacturing. *CIRP Ann - Manuf Technol* 58:9–12. <https://doi.org/10.1016/j.cirp.2009.03.077>
- Witik RA, Payet J, Michaud V, Ludwig C, Manson JAE (2011) Assessing the life cycle costs and environmental performance of lightweight materials in automobile applications. *Compos Part A Appl Sci Manuf* 42:1694–1709. <https://doi.org/10.1016/j.compositesa.2011.07.024>
- Faster cycle, better surface: out of the autoclave : CompositesWorld. <https://www.compositesworld.com/articles/faster-cycle-better-surface-out-of-the-autoclave>. Accessed 17 Apr 2018
- Advani SG, Hsiao K-T (2012) Manufacturing techniques for polymer matrix composites (PMCs). Woodhead Pub
- Henning F, Kärger L, Dörr D, Schirmaier FJ, Seuffert J, Bernath A (2019) Fast processing and continuous simulation of automotive structural composite components. *Compos Sci Technol* 171:261–279. <https://doi.org/10.1016/J.COMPSCITECH.2018.12.007>
- Summerscales J, Searle TJ (2005) Low-pressure (vacuum infusion) techniques for moulding large composite structures. *Proc Inst Mech Eng Part L J Mater Des Appl* 219:45–58. <https://doi.org/10.1243/146442005X10238>
- Hwang S-S, Park SY, Kwon G-C, Choi WJ (2018) Cure kinetics and viscosity modeling for the optimization of cure cycles in a vacuum-bag-only prepreg process. *Int J Adv Manuf Technol* 99: 2743–2753. <https://doi.org/10.1007/s00170-018-2467-y>
- Kay J, Fahrang L, Hsiao K, Fernlund G (2011) Effect of process conditions on porosity in out-of-autoclave prepreg laminates. In: 18Th international conference on composite materials
- Liu S, Li Y, Shen Y, Lu Y (2019) Mechanical performance of carbon fiber/epoxy composites cured by self-resistance electric heating method. *Int J Adv Manuf Technol* 103:3479–3493. <https://doi.org/10.1007/s00170-019-03707-0>
- Crivelli Visconti I, Langella A (1992) Analytical modelling of pressure bag technology. *Compos Manuf* 3:3–6. [https://doi.org/10.1016/0956-7143\(92\)90176-U](https://doi.org/10.1016/0956-7143(92)90176-U)
- Mitchell P, Society of Manufacturing Engineers (1996) Tool and manufacturing engineers handbook. Volume 8, plastic part manufacturing: a reference book for manufacturing engineers, managers, and technicians. In: Society of Manufacturing Engineers
- Park S, Lee D, Song J (2018) Fabrication and evaluation of mechanical properties of carbon/epoxy square tube using pressure bag

- molding and compared with autoclave method. *Int J Precis Eng Manuf* 19:441–446. <https://doi.org/10.1007/s12541-018-0053-8>
17. Drozda T, Wick C, Benedict JT, et al (1983) *Tool and manufacturing engineers handbook: a reference book for manufacturing engineers, managers, and technicians*. Society of Manufacturing Engineers
 18. Dufloy JR, Deng Y, Van Acker K, Dewulf W (2012) Do fiber-reinforced polymer composites provide environmentally benign alternatives? A life-cycle-assessment-based study. *MRS Bull* 37: 374–382. <https://doi.org/10.1557/mrs.2012.33>
 19. Suzuki T, Takahashi J (2005) Prediction of energy intensity of carbon fiber reinforced plastics for mass-produced passenger cars. *Ninth Japan Int SAMPE Symp JISSE-9*:14–19
 20. Song YS, Youn JR, Gutowski TG (2009) Life cycle energy analysis of fiber-reinforced composites. *Compos Part A Appl Sci Manuf* 40: 1257–1265. <https://doi.org/10.1016/j.compositesa.2009.05.020>
 21. Witik RA, Gaille F, Teuscher R, Ringwald H, Michaud V, Manson JAE (2012) Economic and environmental assessment of alternative production methods for composite aircraft components. *J Clean Prod* 29–30:91–102. <https://doi.org/10.1016/j.jclepro.2012.02.028>
 22. Tong R, Hoa SV, Chen M (2011) Cost analysis on L-shape composite component manufacturing. In: *Proc 18th Int Conf Compos Mater* 1–5
 23. Baskaran M, Sarrionandia M, Aurrekoetxea J, et al (2014) Manufacturing cost comparison of RTM, HP-RTM and CRTM for an automotive roof. *ECCM16 16th Eur Conf Compos Mater* 22–26
 24. Vita A, Castorani V, Germani M, Marconi M (2018) Comparative life cycle assessment of low-pressure RTM, compression RTM and high-pressure RTM manufacturing processes to produce CFRP car hoods. *Procedia CIRP*
 25. Potter K, Bloom D, Crowley D, et al (2017) Automating the manufacture of very complex composite structures. In: *ICCM International Conferences on Composite Materials*. pp 20–25
 26. Louis BM (2010) Gas transport in out-of-autoclave prepreg laminates. THE UNIVERSITY OF BRITISH COLUMBIA
 27. Arafath ARA, Fernlund G, Poursartip A (2009) Gas transport in prepregs: model and permeability experiments. *Proc 17th Int Conf Compos Mater* 1–9
 28. Slesinger N, Shimizu T, Arafath ARA, Poursartip A (2009) Heat transfer coefficient distribution. *ICCM 17th*, 27 Jul - 31 Jul 1–10
 29. Anderson JP, Altan MC (2012) Properties of composite cylinders fabricated by bladder assisted composite manufacturing. *J Eng Mater Technol* 134:044501. <https://doi.org/10.1115/1.4007017>
 30. Kar KK (2016) *Composite materials: processing, applications, characterizations*. Springer Berlin Heidelberg, Berlin
 31. Vita A, Castorani V, Mandolini M, Papetti A, Germani M (2019) Cost and temperature homogeneity optimization of the heating system for composite materials air press molding. *Comput Des Appl* 16:1084–1097. <https://doi.org/10.14733/cadaps.2019.1084-1097>
 32. ISO-International Organization for Standardization (2006) *Environmental management—life cycle assessment—principles and framework*. ISO EN:14040
 33. ISO-International Organization for Standardization (2006) *Environmental management—life cycle assessment—requirements and guidelines*. ISO EN 14044
 34. Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B (2016) The ecoinvent database version 3 (part I): overview and methodology. *Int J Life Cycle Assess* 21:1218–1230. <https://doi.org/10.1007/s11367-016-1087-8>
 35. Duverlie P, Castelain JM (1999) Cost estimation during design step: parametric method versus case based reasoning method. *Int J Adv Manuf Technol* 15:895–906. <https://doi.org/10.1007/s001700050147>
 36. Khalil YF (2017) Eco-efficient lightweight carbon-fiber reinforced polymer for environmentally greener commercial aviation industry. *Sustain Prod Consum* 12:16–26. <https://doi.org/10.1016/j.spc.2017.05.004>
 37. (2016) EUROPEAN ALUMINIUM, *Recycling aluminium a pathway to a sustainable economy*. https://www.european-aluminium.eu/media/1712/ea_recycling-brochure-2016.pdf. Accessed 22 Feb 2019
 38. Goedkoop M, Heijungs R, De Schryver A, et al (2013) ReCiPe 2008. A LCIA method which comprises harmonised category indicators at the midpoint and the endpoint level. Characterisation. A life cycle impact ... 133. <http://www.lcia-recipe.net>. Accessed 8 Feb 2019
 39. Solomon S, Qin D, Manning M et al (2007) IPCC, 2007: climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.