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Comparative life cycle assessment of low-pressure RTM, compression RTM and high-pressure RTM manufacturing processes to produce CFRP car hoods

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Abstract

Advanced composite materials, especially those based on carbon fibers, have been attracting the interest of industrial companies for producing light and high-performance components. Resin Transfer Molding (RTM) and its variants have been recognized as the most promising processes to manufacture CFRP (Carbon Fiber Reinforced Polymer) products in a cost-effective way. However, recent research studies highlighted environmental concerns regarding the use of CFRP parts due to the high environmental load related to their production. In this context, the main scope of the present paper is to investigate and compare the environmental impacts of three alternative manufacturing processes for producing CFRP car hoods: RTM, High-Pressure RTM and Compression-RTM. This analysis has been carried out through the standard Life Cycle Assessment methodology. The system boundaries include all the flows related to manufacturing of the hood and an end of life. Results calculated by using the ReCiPe mid-point/end-point method suggest that the eco-friendliest variant is the Compression-RTM.

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Keywords: CFRP car hood; Life Cycle Assessment; RTM; Compression RTM; High-Pressure RTM

1. Introduction

Advanced composite materials, especially those based on carbon fibers, have recently attracted the interest of industrial companies involved in different sectors [1]. Currently, light and high-performance components are not only used in advanced sectors, such as motor racing and aerospace. The use of composite materials has gained the interest of construction, electronic and infrastructure industries for production of lightweight components [2]. This is driving the research in finding innovative production methods that allow decreasing manufacturing costs and times. Indeed, the costs and times related to the traditional autoclave manufacturing process are not suitable for high production volumes or for low-cost components [3]. Out-Of-Autoclave (OOA) methods have been recognized as the most promising processes to produce CFRP (Carbon Fiber Reinforced Polymer) parts in a cost-effective way [4]. In particular, technologies based on dry fibers demonstrated high repeatability, high automation grade and very remarkable performances. Among them, Resin Transfer Molding (RTM) techniques are the most promising ones. Even if these technologies require high investment costs, high-performance products can be produced with a reduced lead time [5].

Recently, the scientific community has been highlighting environmental concerns related to the use of CFRP parts. This is mainly due to high environmental loads generated during the production phase of the base materials (e.g. carbon fibers). Witik et al. [6] proved that the weight reduction reached in automotive carbon fiber components not necessarily lead to enhanced lifecycle environmental performances. Duflou et al. [7] studied the environmental effects of substituting steel

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structures with CFRP alternatives for a reference car design. They concluded that CFRPs can be considered good alternatives only if a long functional life time can be guaranteed. However, they noted the need to improve the production of CFRP base materials, since this phase is an energy intensive process. Raugei et al. [8] used the Life Cycle Assessment (LCA) methodology to compare a range of light-weighting alternatives (aluminum, magnesium and CFRP) for a passenger car. The use of aluminum resulted to be the most capable strategy to reduce environmental impacts. CFRP leads to similar benefits, even if at higher costs, while magnesium is a less interesting alternative.

In recent years, a large number of research studies are focused on analyzing the environmental impacts of Autoclave and OOA processes [9][10]. These studies highlighted that the impregnation phase for manufacturing the base material (i.e. prepreg), on the basis of carbon fibers, requires 40MJ/Kg. This energy is not necessary in case of RTM processes, since dry fibers are used. Moreover, the autoclave molding process is three times more energy intensive with respect to the RTM techniques. A similar result has been reported by Witik et al. [11]. They conducted a study concerning the economic and environmental assessment of different CFRP part production methods: autoclave, VBO (Vacuum Bag Only), and resin infusion in conventional and microwave ovens. The obtained results show that, for the production of a carbon fiber panel, the autoclave is the most expensive and impacting process. By using VBO oven curing it is possible to reduce the costs of 6% in comparison with the autoclave. Moreover, from an environmental point of view, the autoclave showed higher impacts (+10÷20%) with respect to VBO oven curing. They also revealed that the resin infusion process has better economic and environmental performances than VBO, thanks to the lower cost and reduced environmental load generated during the production of the base materials (dry fibers and neat resin vs. prepreg).

However, what emerges from the investigation of the scientific literature is the lack of environmental analyses about the different variants of RTM. Only economic comparisons can be found, such as the study conducted by Baskaran et al [12]. Thus, the main scope of the present paper is to investigate and compare the environmental impacts of Low Pressure-RTM, High Pressure-RTM and Compression-RTM for producing CFRP components. A car hood has been taken as reference part. This analysis has been carried out through the application of the standard LCA methodology, by including the manufacturing and EoL phases within the system boundaries.

2. RTM variants description

OOA methods, in particular RTM and its variants, have been proved to be very promising to shorten cycle times for the production of CFRP parts. In this paper, three different RTM variants are analyzed (Fig. 1): Low Pressure - RTM (LP-RTM), High Pressure - RTM (HP-RTM) and Compression - RTM (C-RTM).

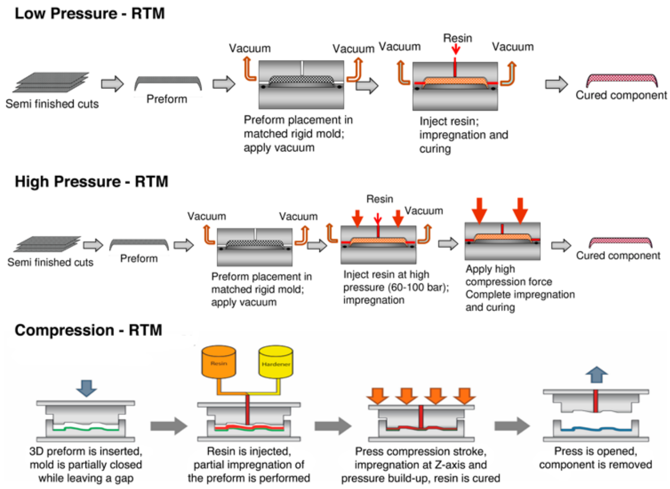

Fig. 1. RTM variants analyzed.

Resin transfer molding is a closed-mold process. In this process, reinforcing dry fibers, often in the form of textile, are placed inside a closed mold, before the injection of a liquid thermoset resin. The resin flows through the cavity ensuring that all the fibers are wetted, and all the air is eliminated (no air voids should be present). The mold is heated, using liquid systems, induction systems or hot platens, to the adequate temperature that allows the matrix curing [13].

LP-RTM [14] is a modification of the conventional RTM process. It employs lower resin injection pressure and final hydrostatic pressure during the curing cycle. Vacuum is used to clamp molds and helps the resin flow across the fiber pack. The standard cycle time has a duration of 30-60 minutes, considering the typical injection pressure of 10-20bars. The typical content of fiber ranges from 60 to 65%. This method has the advantage to use cheaper tooling in comparison to traditional RTM or other closed molding processes.

HP-RTM [15] aims to reduce the RTM cycle time to less than 10 minutes. High pressure levels, up to 150bars in the mixing head and 30-120bars inside the mold, are exploited. The resin injection system is an impingement mixing head. The use of high pressures allows reaching great fiber content, up to 70%. The main disadvantages of HP-RTM are mainly related to high costs of tooling and possible shifts of dry fibers, caused by the high pressure. The latter effect can potentially lead to lower mechanical performances of the part.

C-RTM [16] was born to further reduce cycle times and produce parts with a high fiber content (up to 60%) avoiding fibers distortion. In the C-RTM method, during the injection phase, the mold is not fully closed. A gap exists between the dry preform and the mold upper part. The flow path is wider and offers less resistance to the resin flow, thus the injection pressure can be decreased to 5-10bars, preventing issues related to fiber distortion. This leads to low injection and impregnation time, resulting in reduced cycle time respect to the HP-RTM. Moreover, since flow resistance is lower, the resin can be injected faster. This is a key advantage of this RTM variant. Once the resin is completely injected, the mold is closed, and the curing process starts. The main difficulty of C-RTM is to guarantee that all the fiber bundle is fully coated with resin in order to avoid dry spots.

3. Life cycle assessment

3.1. Goal and scope definition

The objective of this LCA study, compliant with the ISO 14040 [17] and ISO 14044 [18] standards is to compare three different manufacturing processes for the production of a CFRP car hood. The latter is a hood mounted in an Italian luxury car. The shape is flat with a surface of 1,47m^2.

The functional unit is defined as "the production of 1000 CFRP car hoods through three alternative production processes: (i) LP-RTM, (ii) HP-RTM, and (iii) C-RTM".

This study is a gate to gate analysis. The system boundaries include the material extraction, manufacturing and End-of-Life (EoL) phases for those flows directly involved in the operation of the three alternative processes (Fig. 2). Concerning this, for example, the carbon fibers and the matrix system have been excluded, as well as the impact related to the transportation and the cutting of the carbon fibers.

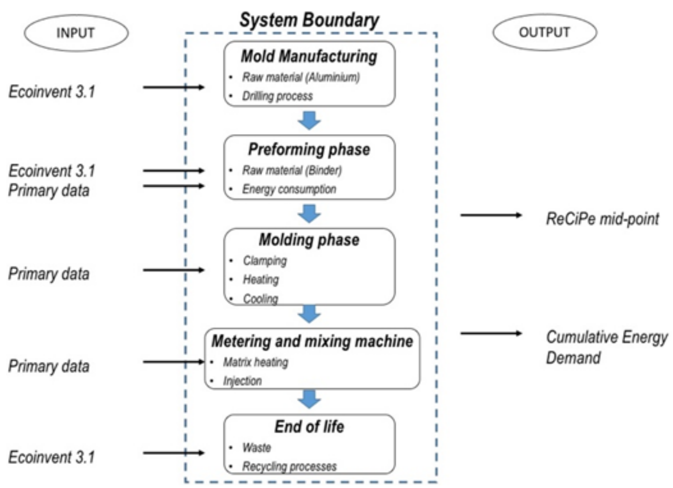

Fig. 2. System boundaries for C-RTM and LP-RTM processes.

The processes present consistent differences, especially in terms of molds size. This is due to the different operating injection and in-mold pressures. Molds for the C-RTM are designed to withstand a clamping force less than 10tons, while molds for HP-RTM must resist to values higher than 500tons. This leads to the use of HP-RTM molds weighing more than double with respect to the C-RTM or LP-RTM molds. As a consequence, the energy consumed by the pumps for closing the press platens is higher in the HP-RTM than the LP-RTM and C-RTM. At the same time, if comparable cycle times for the three processes are guaranteed, in case of HP-RTM the heat necessary for keeping molds at the cure temperature is the highest, due to their higher thermal inertia. In the wake of this, also the cooling phase presents differences among the three processes. In order to avoid shape distortions of the CFRP component, the extraction phase must be performed at a temperature lower than the Tg (glass transition temperature) of the matrix. Therefore, the cooling of the C-RTM molds will require less energy than the other methods.

Other differences can be found analyzing the preforming phase. In the HP-RTM, the high-pressure flow of the matrix in the preform can results in fibers distortion. To avoid this, high binder concentrations must be used, leading to slower and more energy consuming preforming. Differently, in the C-RTM and LP-RTM processes the binder concentration can be lower and, thus, less energy is necessary for its curing.

Finally, the energy consumptions of the metering and mixing machine will be different for each process. In the HP-RTM, the matrix must have the lowest possible viscosity to penetrate in the preform and this can be guaranteed by increasing the injection temperature as these quantities are inversely proportional. Even if the temperature cannot be increased beyond a certain limit, to avoid the premature polymerization of the matrix, its value is generally higher than in the case of low-pressure processes. This implies a greater energy consumption for heating the matrix in the metering and mixing machine. Moreover, to reach the high injection pressure typical of the HP-RTM (more than 100bars), pumps with high power absorption are necessary. In the C-RTM, thanks to the injection in the gap over the preform, the injection pressure is lower than 10bars and small size pumps are used. In the LP-RTM, with a typical injection pressure of 10-20bars, small and mid-size pumps are preferred.

For the purpose of this study, both primary and secondary data have been used. Primary data have been collected in collaboration with an Italian company, leader in the production of CFRP components for the automotive market. These data are related to the C-RTM and the LP-RTM processes that are ordinarily performed in the company production plant with automatic lines. Data have been measured from the preforming station, molding station, and metering and mixing machine. The measures about electric energy consumptions have been realized by using the PQA824 power analyzer by HT instruments. For raw materials extraction, molds manufacturing processes and EoL phase, background data from a commercial LCA database (Ecoinvent 3.1) have been used. The energy consumptions related to the HP-RTM process, as well as the size of the mold have been estimated on the basis of literature data and with the support of the involved company.

Regarding simplifications, a cut-off mass of 20g has been applied to all the material flows. In addition, as can be seen in Fig. 2, manufacturing of the presses and their ancillary equipment have not been considered. This choice is justified by the longer life time of equipment, compared to the period needed for manufacturing 1000 hoods. For this reason, the impacts allocated to machine construction can be considered negligible, as demonstrated in previous studies [19].

3.2. Life cycle inventory

This section presents the information and data used for the LCA analysis of the three processes.

3.2.1. Inventory data collection for raw material and manufacturing in mold manufacturing phase

The inventory related to raw material extraction and manufacturing phases for the molds is presented in Table 1. The weight of the mold for HP-RTM has been estimated, while for C-RTM and LP-RTM derives from real measurements. According to indications provided by the involved company, the life cycle of the molds before they need maintenance has been set to 1500 cycles.

The chosen allocation model is the "Allocation, recycled content System Model" (Alloc Rec, S). In this model, recyclable materials are available burden-free to recycling processes [20]. Datasets used for materials refer to an unspecified location in the world (GLO and RER). This choice derives from the fact that the manufacturer buys raw materials in different geographic areas of the world.

Table 1. Datasets and quantities used to model the molds.

EcoInvent 3.1 dataset	LP-RTM	HP-RTM	C-RTM
Aluminium, primary, ingot {GLO}| market for | Alloc Rec, S;	500kg	1200kg	300kg
Aluminium removed by milling, large parts {RER}| aluminium milling, large parts | Alloc Rec, S	47kg	68kg	30kg

3.2.2. Inventory data collection for preforming, molding and injection phases

Data related to the preforming, molding and injection phases have been collected by direct measures for C-RTM and LP-RTM, therefore they can be considered as primary data. The same data have been estimated for the HP-RTM. The measurements have been carried out without considering the transient phases when the molds and the matrix are at room temperature. Only the temperature variation from the value set for the extraction of the component to the value set for the curing and vice versa have been considered.

The datasets and quantities used in this analysis are reported in Table 2.

Table 2. Datasets and quantities used to model the production of 1 CFRP hood.

	EcoInvent 3.1 dataset	LP-RTM	HP-RTM	C-RTM
Binder	Epoxy resin, liquid {GLO}| market for | Alloc Rec, S	36g	60g	30g
Preforming	Electricity, medium voltage {IT}| market for | Alloc Rec, S	1,7kWh	1,9kWh	1,7kWh
Molding	Electricity, medium voltage {IT}| market for | Alloc Rec, S	15,93kWh	28,78kWh	5,71kWh
Mixing and metering machine	Electricity, medium voltage {IT}| market for | Alloc Rec, S	2,3kWh	2,9kWh	1,4kWh

3.2.3. Inventory data collection for Eol phase

The EoL treatments have been chosen among the "Recycling treatments" and "Landfill" categories included in Ecoinvent 3.1 database. The only parts to recycle are the molds. The amount of the recyclable mass of the aluminum has been set to 98%. This high value for the recycling rate (higher than the average recycling rate of the aluminum recycling chain [21]) has been set considering that the mold has a monolithic structure (i.e. single material) and thus can be easily recycled with low losses. We have then considered only a 2% of process inefficiency, with residual wastes that are landfilled. This value is based on the estimation that ancillary materials, such as fittings, ejectors, injectors and so on (which constitute about the 2% in weight of the mold), cannot be recovered due to the presence of cured resin.

To include the benefits deriving from the recycling of materials, the recycled material has been included as "avoided product" in the EoL process modelling. For what concern the leftover parts and masses, which remain as wastes, the following dataset has been used:

- Municipal solid waste (waste scenario) {RoW}, treatment of municipal solid waste, landfill, | Alloc Rec, S.

3.3. Results assessment and interpretation

The LCA analysis has been carried out using SimaPro 8.05.13 as software tool and the database EcoInvent 3.1 as supporting inventory database.

The methods used to calculate the environmental impacts are the following:

- ReCiPe mid-point - Hierarchist (H) version - Europe life cycle impact assessment (LCIA) [22];
- ReCiPe end-point - Hierarchist (H) version - Europe H/A - with the average weighting set (A) [22];
- Cumulative Energy Demand (CED) [23].

ReCiPe mid-point (H) method contains, in the climate change impact category, all greenhouse gases described in the Kyoto Protocol utilizing global warming potentials from the IPCC Fourth Assessment Report within a timeframe of 100 years [24]. The Hierarchist (H) version of the ReCiPe mid-point and end-point method refers to the normalization values of Europe and is founded on the most common policy principles with regards a time horizon of 100 years [18]. The CED impact category applies the 'energy harvested' concept on all energy resources, i.e. renewable, fossil and nuclear [23].

The comparison between the three different RTM variants (LP-RTM, HP-RTM and C-RTM), in terms of mid-point categories, is shown in Fig. 3. It is possible to note that the main impacts, in all the RTM variants and in all the impact categories (except Ozone depletion) is due to the mold.

The binder is the item that has the least impact in every process variant and damage category. However, considering that the quantity of binder used is minimal (maximum 60g for HP-RTM), its contribution is not negligible and for some impact categories (e.g. photochemical oxidation formation), it reaches almost 2%. The greatest contribution is in the case of HP-RTM being the binder quantity used greater.

Contrary to what might be thought, the contribution of the molding phase to the environmental damages (especially for the HP-RTM) is not so impactful if compared to the mold manufacturing.

Another aspect worth of attention is that the raw material used for the manufacturing of the mold can be recycled up to 98%, contributing to the mitigation of the total environmental load. If the recycling rate was set to a lower value, the total damage produced would have been higher for all the three processes. This highlights the need to better investigate the EoL modelling in future work.

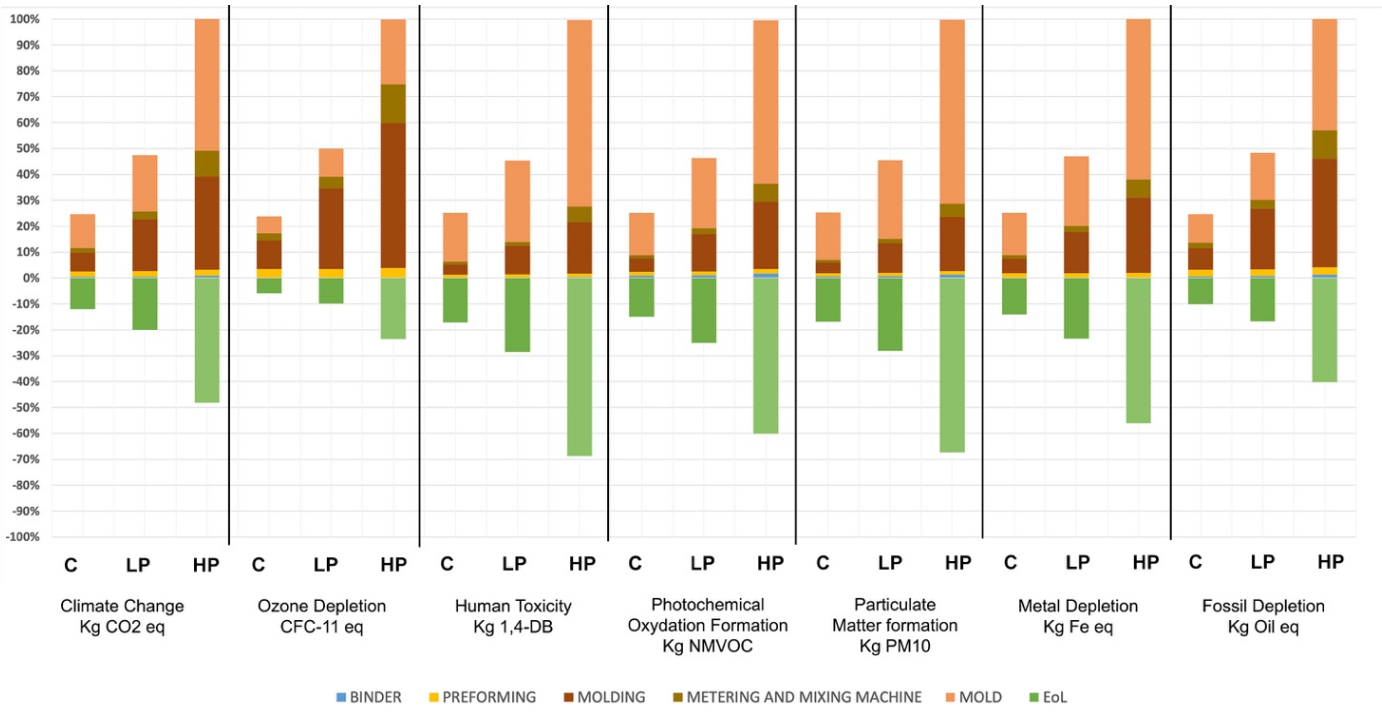

Fig. 3. Comparison of the RTM variants in terms of ReCiPe mid-points.

The preforming phase is responsible for a greater percentage contribution in the HP-RTM if compared to the other variants. The same consideration can be also derived for the metering and mixing machine.

Fig. 4 shows the results in terms of end-points. Compression RTM is the eco-friendliest process variant, followed by Low Pressure RTM and High-Pressure RTM, for all the three damage categories. The reduced curing time (if compared to LP-RTM) and the lower pressure (if compared to HP-RTM), determine a considerable reduction of energy consumption, leading to less environmental impacts. In particular, a reduction of about 47% is observed by comparing the HP-RTM and the LP-RTM. A further reduction of about 19% can be obtained passing from LP-RTM to C-RTM.

The same conclusions can be drawn if CED results are analyzed (Fig. 5).

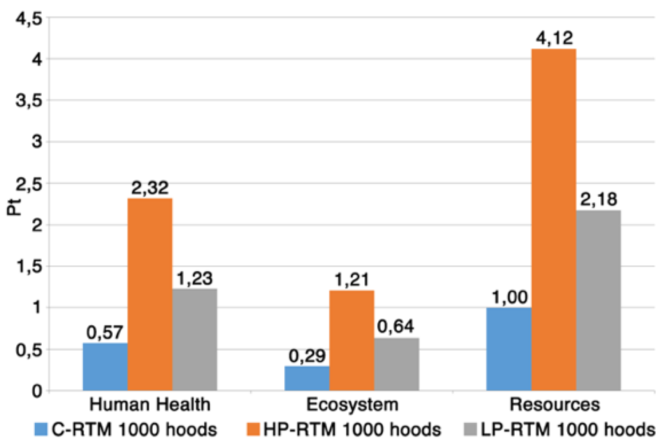

Fig. 4. Comparison of the RTM variants in terms of ReCiPe end-points.

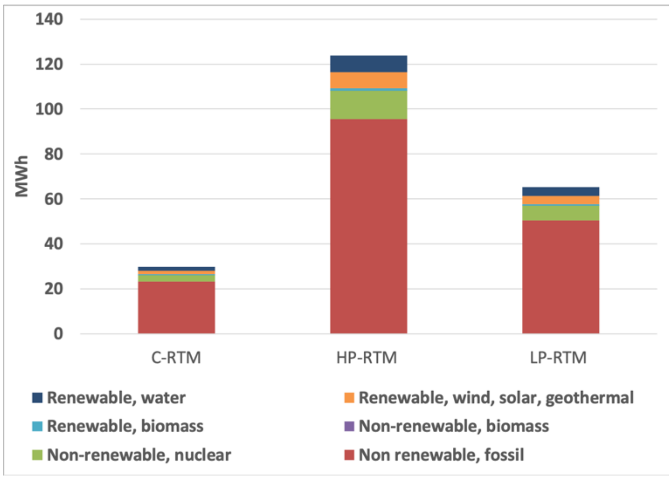

Fig. 5. Comparison of the RTM variants in terms of CED.

4. Discussion and Conclusions

The results presented in the previous section show a comparison of the environmental impacts of three Resin Transfer Molding variants. These impacts have been evaluated exploiting the ReCiPe impact assessment method both at mid-point and end-point levels, and the CED. The principal aim of this research was to better understand the potentiality of RTM processes in reducing environmental impacts of composite manufacturing and, analyzing the breakdown of the impacts for each indicator, where the focus must be pointed out for reaching this goal.

What emerges from the analysis is that the highest contribution for all the processes mainly derives from the manufacturing of the mold, where a great amount of aluminum is used. The environmental damage produced is relevant, but not so high as can be expected. However, it plays a fundamental indirect role in the molding phase. As explained above, the mold size directly influences the energy consumption of the heating and cooling systems. It was not possible to separately measure the phases of heating, cooling and clamping but only an aggregated value was considered. However, through analytical calculations, it is possible to estimate that the contribution of the clamping system is the less relevant if compared to the heating and cooling.

According to the processes analyzed, it is evident that moving towards low pressure methods, such as C-RTM or LP-RTM, a drastic reduction of impacts caused by the manufacturing of CFRP components can be obtained. The molding phase should be deeply analyzed in order to reduce the amount of electricity needed, for example by using more efficient heating methods and materials.

What is important to underline is that this study is only a comparative analysis from an environmental point of view and other indicators should be evaluated to identify the best RTM process. Then, for a more exhaustive analysis, also the performances of the products, as exposed in [25], and the economic aspects, as shown in [26], should be taken into consideration. However, this can be considered as the first step toward a more detailed study.

Future work will consist in collecting primary data also for the HP-RTM process. Moreover, system boundaries could be enlarged to take into consideration also the press system that in the case of HP-RTM can reach the 5000tons.

References

[1] Holmes M. Carbon composites continue to find new markets. Reinf Plast 2017;61:36–40. doi:10.1016/j.repl.2016.12.060.

[2] Mathes V. The composites industry: plenty of opportunities in heterogeneous market. Reinf Plast 2018;62:44–51. doi:10.1016/J.REPL.2017.05.002.

[3] Rao S, Simha TGA, Rao KP, Ravikumar GV V. Carbon Composites Are Becoming Competitive And Cost Effective. Infosys Website 2015:2–3.

[4] Holmes M. Carbon fibre reinforced plastics market continues growth path. Reinf Plast 2013;57:24–9. doi:10.1016/S0034-3617(13)70186-3.

[5] Laurenzi S, Marchetti M. Advanced Composite Materials by Resin Transfer Molding for Aerospace Applications. Compos Their Prop 2012:197–226. doi:10.5772/2816.

[6] Witik RA, Payet J, Michaud V, Ludwig C, Månson JAE. Assessing the life cycle costs and environmental performance of lightweight materials in automobile applications. Compos Part A Appl Sci Manuf 2011;42:1694–709. doi:10.1016/j.compositesa.2011.07.024.

[7] Duflou JR, De Moor J, Verpoest I, Dewulf W. Environmental impact analysis of composite use in car manufacturing. CIRP Ann - Manuf Technol 2009;58:9–12. doi:10.1016/j.cirp.2009.03.077.

[8] Raugei M, Morrey D, Hutchinson A, Winfield P. A coherent life cycle assessment of a range of lightweighting strategies for compact vehicles. J Clean Prod 2015;108:1168–76. doi:10.1016/j.jclepro.2015.05.100.

[9] Song YS, Youn JR, Gutowski TG. Life cycle energy analysis of fiber-reinforced composites. Compos Part A Appl Sci Manuf 2009;40:1257–65. doi:10.1016/j.compositesa.2009.05.020.

[10] Suzuki T, Takahashi J. Prediction of energy intensity of carbon fiber reinforced plastics for mass-produced passenger cars. Ninth Japan Int SAMPE Symp JISSE-9 2005:14–9.

[11] Witik RA, Gaille F, Teuscher R, Ringwald H, Michaud V, Manson JAE. Economic and environmental assessment of alternative production methods for composite aircraft components. J Clean Prod 2012;29–30:91–102. doi:10.1016/j.jclepro.2012.02.028.

[12] Baskaran M, Sarrionandia M, Aurrekoetxea J, Acosta J, Argarate U, Chico D. Manufacturing cost comparison of RTM, HP-RTM and CRTM for an automotive roof. ECCM16 16th Eur Conf Compos Mater 2014:22–6.

[13] Advani SG, Hsiao K-T. Manufacturing techniques for polymer matrix composites (PMCs). Woodhead Pub; 2012.

[14] Davenport DE, Petrovich R, Sutton G. Low Pressure Resin Transfer Molding for Cost Effective Aircraft Quality Structures 2007.

[15] R. Chaudhari, P. Rosenberg, M. Karcher, S. Schmidhuber, P. Elsner FH. HIGH-PRESSURE RTM PROCESS VARIANTS FOR MANFUACTURING OF CARBON FIBER REINFORCED COMPOSITES. 19Th Int. Conf. Compos. Mater., n.d.

[16] Bhat P, Merotte J, Simacek P, Advani SG. Process analysis of compression resin transfer molding. Compos Part A Appl Sci Manuf 2009;40:431–41. doi:10.1016/j.compositesa.2009.01.006.

[17] ISO-International Organization for Standardization. Environmental management - Life cycle assessment - Requirements and guidelines. ISO EN 14044 2006.

[18] ISO-International Organization for Standardization. Environmental management - Life cycle assessment - Principles and framework. ISO EN 14040 2006.

[19] Favi C, Germani M, Mandolini M, Marconi M. PLANTLCA: A Lifecycle Approach to Map and Characterize Resource Consumptions and Environmental Impacts of Manufacturing Plants. Procedia CIRP 2016;48:146–51. doi:10.1016/J.PROCIR.2016.03.102.

[20] Nicholson AL, Olivetti EA, Gregory JR, Field FR, Kirchain RE. End-of-life LCA allocation methods: Open loop recycling impacts on robustness of material selection decisions. 2009 IEEE Int. Symp. Sustain. Syst. Technol., IEEE; 2009, p. 1–6. doi:10.1109/ISSST.2009.5156769.

[21] European Aluminium, https://www.european-aluminium.eu/media/2275/european-aluminium-press-release-2015canrecyclingresult.pdf.

[22] Goedkoop M, Heijungs R, De Schryver A, Struijs J, van Zelm R. ReCiPe 2008. A LCIA method which comprises harmonised category indicators at the midpoint and the endpoint level. Characterisation. A Life Cycle Impact … 2013:133. doi:http://www.lcia-recipe.net.

[23] Frischknecht R, Wyss F, Büsser Knöpfel S, Lützkendorf T, Balouktsi M. Cumulative energy demand in LCA: the energy harvested approach. Int J Life Cycle Assess 2015;20:957–69. doi:10.1007/s11367-015-0897-4.

[24] Solomon S, Qin D, Manning M, Al. E. Climate Change 2007: The Physical Science Basis. Contrib Work Gr I to IV Assessmente Rep Intergov Panel Clim Chang 2007.

[25] Castorani V, Rossi M, Germani M, Mandolini M, Vita A. Life Cycle Assessment of Home Smart Objects: Kitchen Hood Cases. Procedia CIRP 2018;69:499–504. doi:10.1016/j.procir.2017.11.113.

[26] Favi C, Raffaeli R, Germani M, Gregori F, Manieri S, Vita A. A life cycle model to assess costs and environmental impacts of different maritime vessel typologies. Proceedings of the ASME Design Engineering Technical Conference; Volume 4, 2017. doi: 10.1115/DETC2017-68052