A combined finite element – Life cycle assessment approach for assessing the sustainability of the thermoforming process of a thermoplastic composite component

STAMOPOULOS Antonios G.[1,a*], LA ROSA Angela Daniela[2,b] and CREONTI Gianluigi[3,c]

[1]Department of Industrial and Information Engineering and Economy (DIIIE), University of L'Aquila, Via Giovanni Gronchi, 18, Nucleo Industriale Pile L'Aquila, 67100, Italy

[2]Department of Manufacturing and Civil Engineering, Norwegian University of Science and Technology, Gjøvik 2815, Norway

[3]Crossfire srl, Via Corona, 1, 48027, Solarolo, Ravenna, Italy

[a]antonios.stamopoulos@univaq.it, [b]angela.d.l.rosa@ntnu.no, [c] g.creonti@crossfire-srl.com

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Abstract. Nowadays, thermoplastic-based composite materials are catching up in many industrial sectors due to their unique features, especially their recyclability, their lower requirements regarding their storage and the fact that may be heated-up and formed into a definitive product. To this end, the thermoforming process appears to be an appealing fabrication process. However, throughout this process, a number of defects may be introduced that can affect the morphology and structural performance of the product. Until recently, the definition of the optimal process characteristics was based on trial-and-error experimental tests that increased the resources required for its development. In addition, a significant part of the thermoplastic composite plate has to be removed/wasted after the thermoforming process. In this work, a well-established numerical methodology is applied to an industrial thermoplastic composite component. After considering an initial thermoplastic composite plate, the effect of the reduction of the overall dimensions, without compromising the product quality, on the environmental footprint is considered. To perform this task, a finite element (FE) simulation is utilized for assessing the possibility to reduce the plate dimensions without introducing defects while, in parallel, a life cycle assessment (LCA) is put into practice. Through the synergy between the 2 disciplines, useful insights are provided regarding the effectiveness of the fabrication process by defining the composite plate dimensions that contributes to the amelioration of the environmental footprint with the minimum expense on the component quality.

Introduction

Thermoplastic composite materials are considered as an appealing solution for producing lightweight components due to their unique features they exhibit such as their recyclability and the existence of a variety of well-established manufacturing production processes [1]. Among them, there can be distinguished the injection molding [2-3] for short-fiber reinforced composites, the compression molding [2] and thermoforming [4]. Especially the last one, copes with the deformation of a semi-finished, previously impregnated, composite lamina under a combined pressure-temperature cycle inside the cavity of the molds (punch and mold tools). After the extraction of the permanently deformed shape, the out-of-figure part is removed, and the definite product may be obtained [4-5]. Even though this method is currently applied to industrial products, the quality of the final component is a critical issue since intense shearing, wrinkles, residual stresses, and thickness variations may be introduced [5]. Therefore, the majority of the scientific

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research utilized benchmark geometries for further study and for ameliorating the predictability of the existing numerical tools. Following up this strategy, in the past few years, FE tools and numerical methods have been introduced that enabled the accurate prediction of these defects and, consequently, the definition of the optimal process parameters for minimizing them [4-5]. These parameters are mostly related to the temperature cycles, the applied pressure, the geometry orientation of the cavity of the molds, the stamping speed, and the auxiliary equipment [6].

On the other hand, the energy and resource efficiency of the process chain needs to be guaranteed as they contribute to the so-called climate neutral economy [7-8]. To this end, the life cycle assessment is a versatile method for addressing the impact of the semi-finished or definite products, considering factors such as materials, consumables, and energy requirements for fabricating these products [8]. Considering the characteristics of the abovementioned processes chain, the life cycle assessment may be a useful tool for quantifying the environmental impact of the variation of some process parameters.

In the present work, the LCA technique is employed in an industrial case study for quantifying the environmental impact while producing a thermoplastic composite component for the automotive sector. In parallel, an FE simulation campaign is conducted for defining the optimal process parameters and for excluding the experimental trial-and-error tests. In addition, the effect of the reduction of the composite plate dimensions, prior to the thermoforming process, reducing the material waste as well, and for increasing the product units per lamina by 1 is considered. By the synergy of these methods/disciplines, it was found a significant decrease of the environmental impact while reducing the composite plate dimensions prior to the thermoforming process, even though the material waste may be considered recyclable.

Methodology, Manufacturing and Assumptions

The basic concept of the methodology of the present work is presented in Figure 1 and may be further divided into 3 main parts, namely the manufacturing of the component that includes all the fabrication chain processes, the finite element simulation for defining the thermoforming process parameters and the life cycle assessment. There should be noted that the present methodology was applied to an already-existing industrial equipment and, therefore, the restrictions regarding the machinery, relative production capacity (dimensions of the impregnated lamina, applied pressures, heating systems etc.) as well as the energy consumption are defined by the industrial partner. Consequently, the present work deals with an actual industrial case starting from raw materials and ending to the production of the finished product.

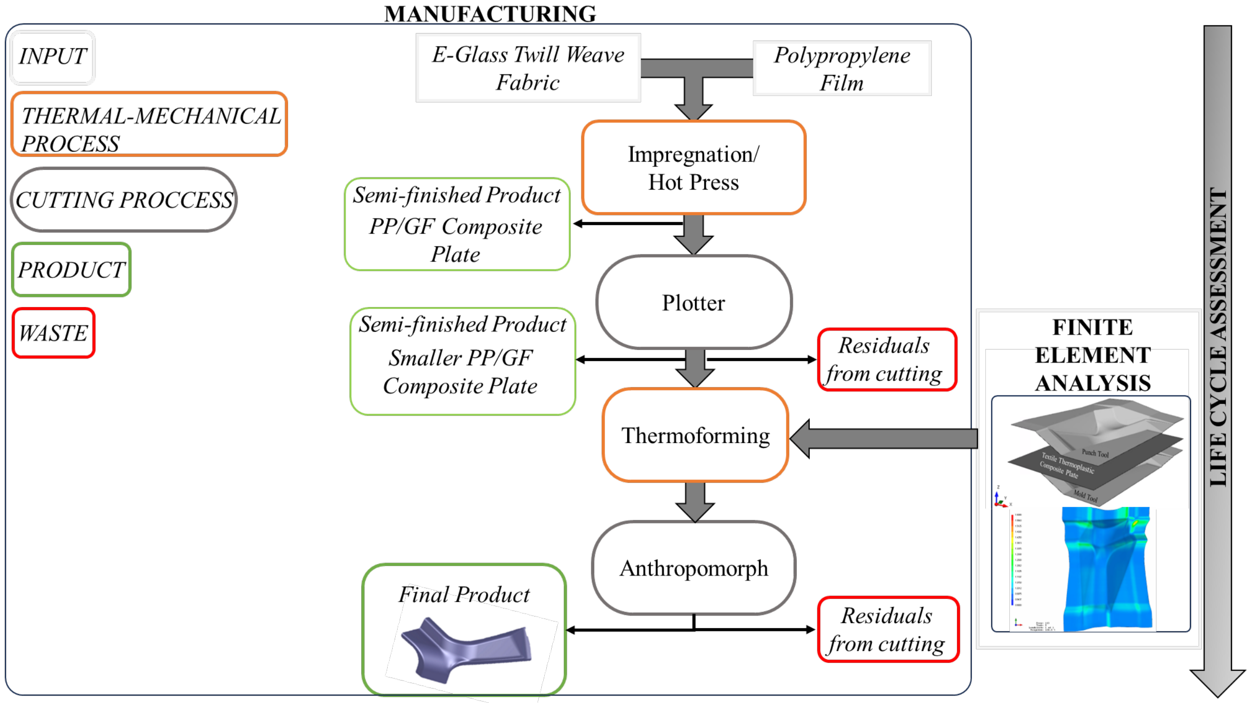

Figure 1: The outline of the methodology of the study performed in the present work.

Manufacturing of the Thermoplastic Composite Component

Before the thermoforming process, the initial Woven Textile E-glass/PP composite plate should be produced using the hot-pressing impregnation process where 2 films of polypropylene are combined with the E-glass fabric. After applying 20 kg/cm^2 of pressure for 40 seconds at 200 °C, a 4 m long and 0.7 wide mono-layer semi-finished composite plate (commercial name: CrossLam GppBx600 0/90) is obtained. Consecutively, a plotter is used for producing smaller rectangular plates that are thermoformed afterwards. Besides the production of smaller plates, a quantity of waste is obtained as residual from the process chain up to this point.

Regarding the main fabrication part (thermoforming), the process parameters such as the stamping speed and material temperature are defined by the finite element simulation. Using the finite element methodology presented in past works [6, 9] the dimensions of the small plates prior to the thermal forming are considered. This part is crucial since the dimensions of the composite plate define the waste that is produced at this point and the number of products that are extracted from the initial 4 x 0.7 [m] composite lamina. The equipment for conducting the thermoforming process considered by industrial part of the present study is composed of:

- A 4 axis press machine where the aluminium molds are placed.
- The molds that are heated up to 110 °C using heated oil through a pump system. The hot oil flows close to the external surfaces of the moulds. Once the target temperature is achieved, the system may be considered as isothermal since the losses are negligible and no continuous heating is required.
- A system of 4 couples of 2 kW infrared lamps for heating the composite material up to the temperature defined by the outcome of the FE simulation. In the present work, the material temperature is considered at 190 °C.
- No additional auxiliary equipment, such as tensioners, is considered.

Once the process is completed, the final product is extracted from the thermoformed composite plate using an anthropomorph cutter. Therefore, not only the final component is obtained but also the out-of-figure waste as well.

Definition of the Process Parameters Through Finite Element Analysis
Considering the abovementioned characteristics of the process chain, an essential part is the definition of the thermoforming process parameters such as the material temperature under an already-defined stamping speed. In addition, for reducing the overall waste and for exploring the possibility of producing more components, the characteristics of the thermoformed product, in terms of residual stresses, probability of wrinkles formation and thickness variation, are addressed while reducing the dimensions of the smaller composite plates. Therefore, the role of the process simulation is about providing information regarding the product quality while reducing the dimensions of the thermoplastic composite plate. This task is performed using a well-established and accurate FE methodology [6,9] using the Aniform™ FE code [10]. The geometry of the stamping and mold tools are presented in Figure 2. The material model is the one of a PP/GF balanced twill weave material with the same content as the one of interest in the present work, seen in [6]. The thermoforming simulation is conducted using membrane elements LTR3D membrane elements and the DKT (Direct Kirchhoff Triangle) shell elements where the in-plane shear and bending behaviour of the heated-up composite material are enclosed. Contact elements are placed at the top and bottom of the plate that enclose the dynamic friction behaviour of the composite material (tool-composite).

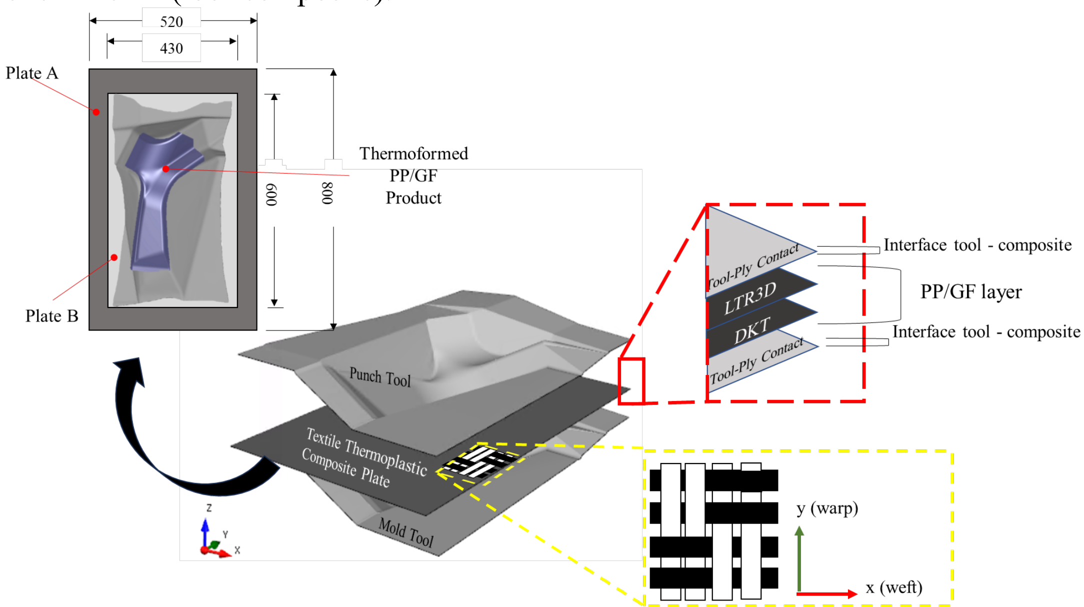

Figure 2: The FE model set-up for simulating the thermoforming process and the dimensions of the 2 plates considered.

The process is considered as isothermal while no cooling-down of the material is considered. Moreover, as seen in Fig. 2, the plate is oriented towards the y axis (warp). In addition, a complete and perfect closing of the molds is assumed, and no vacuum is present in order to comply with the production requirements of the industrial partner. After a parametric study of the mesh and the various material temperatures (160 ºC, 190 ºC) the characteristics of the thermoformed plate in terms of probability of wrinkles formation, stresses, shearing, and thickness variation are evaluated. Consequently, the thermoforming temperature is defined at 190 ºC which is consistent with past works using similar materials for achieving satisfactory results: no wrinkles are present in the area of the final product and not higher textile shearing as well. The validity and robustness of the above-mentioned simulation methodology was previously validated in other applications as seen in past works [11-12] where the same material was studied.

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Objectives and Assumptions for Life Cycle Assessment
Life Cycle Assessment (LCA) is a tool that was developed to evaluate the environmental aspects and potential impacts (e.g., use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal (i.e., cradle-to-grave). The LCA methodology follows the ISO 14040-44 [13] and is structured in four main phases in an LCA study presented in Fig.3.

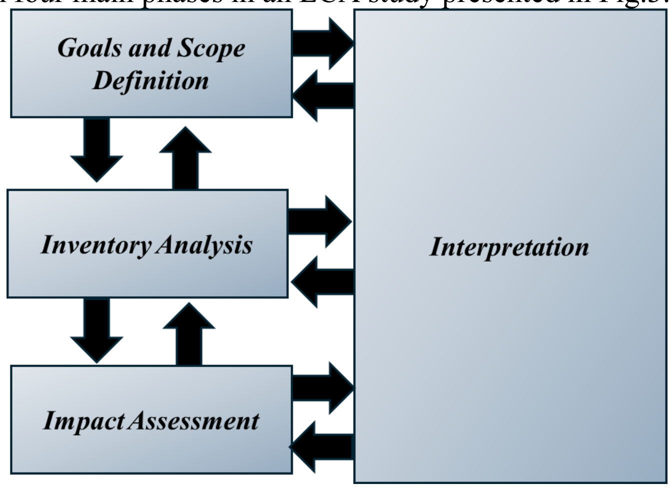


Figure 3: The interaction between the main phases of the life cycle assessment (LCA).

The Goal and Scope definition phase includes:
- intended application of the study, reasons for carrying out the study, intended audience,
- product system,
- the functional unit; the system boundary; allocation procedures,
- the impact categories selected: methodology of impact assessment,
- data requirements; assumptions; limitations.

The Inventory analysis phase includes:
- data collection,
- calculation.

Impact assessment phase includes:
- selection of impact categories, category indicators and characterization model,
- assignment of Life Cycle Inventory (LCI) results to the selected impact categories, (classification)
- calculation of category indicator result (characterization).

Interpretation phase
- identification of the significant issues based on the results of the LCI and the Life Cyle Impact Assessment (LCIA) phases of the LCA,
- an evaluation that considers completeness, sensitivity, and consistency checks,
- conclusions, limitations, and recommendations.

LCA is an iterative approach where the individual phases use results from the other phases, as seen in Fig. 3. This approach leads to comprehensiveness and consistency of LCA studies and the reported results. However, LCA address potential environmental impacts but does not predict absolute or precise environmental impacts. This is, among other things, due to the relative expression of potential environmental impacts to a reference unit, the inherent uncertainty in modelling of environmental impacts and the fact that some possible environmental impacts are future impacts.

Comparative Life Cycle Assessment Inventory

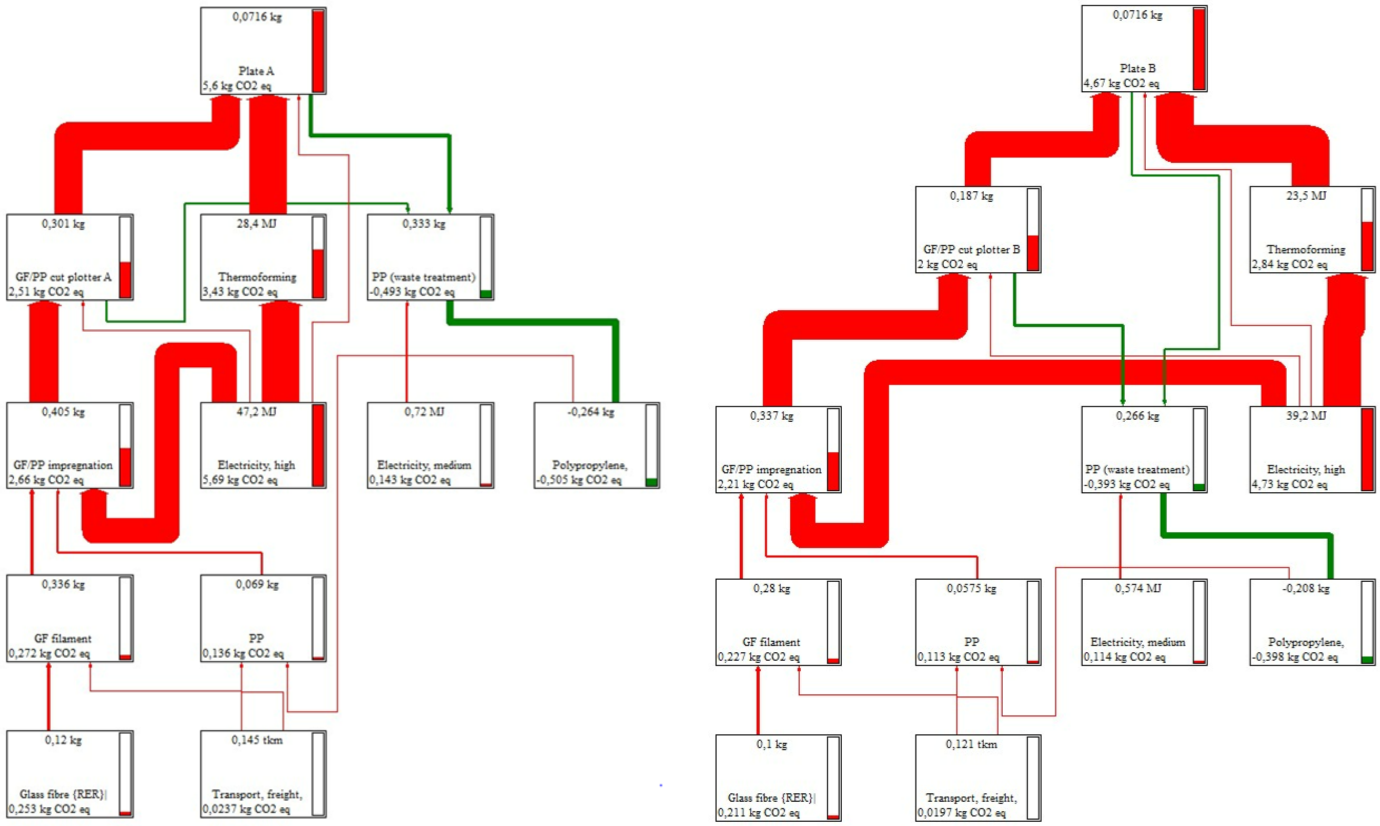
The goal of the study is to conduct a comparative LCA of two plates (plate A and plate B) produced with the same materials and for the same function and final weight, but with different size. The difference between them may be observed in Fig.2 of the present work. Size optimization was performed by means of FEM analysis as seen in the previous section. The functional unit is defined as 1 plate with dimensions 0.8 x 0.52 x 0.5 [m] for Plate A and 0.6 x 0.43 x 0.5 [m] for Plate B respectively while the final product weight is 71,6 gr. Considering the dimensions of the plate A and B, 5 plates may be extracted from the initial lamina in the case of Plate A while 6 plates may be extracted in the case of Plate B. Inventory data of materials and energy consumption are reported in Table 1. The plates were extracted with a plotter from a GFRP laminate made through impregnation and hot-pressing of E-glass fiber textile (600 gr/m^2 x 2.8 m^2= 1680 gr.) with polypropylene (2 films 345 gr in total). All the data regarding the energy consumption are related to the equipment/machine utilized are provided by the industrial partner (Crossfire srl, Solarolo, Italy).

Table 1: Inventory data of materials and energy consumption for the scenarios A and B.

Scenario/ Plate	Process	Machine	Energy Consumption [kWh]	Output	Material Quantity [gr]	Waste [gr]
A	**Impregnation**	Continuous Press + Heating	25.9	1 monolayer plate	2025	-
	Cutting in Plotter	Plotter	0.08	5 plates A	1505	520
	Thermoforming of A at 190 ºC	Hot Press + IR Lamps	7.89	1 thermoformed plate A	301	-
	Cutter	Anthropomorph	0.012	*Final Product*	*71.6*	229.4
B	**Impregnation**	Continuous Press + Heating	25.9	1 monolayer plate	2025	-
	Cutting in Plotter	Plotter	0.08	6 plates B	1122	903
	Thermoforming of B at 190 ºC	Hot Press + IR Lamps	6,54	1 thermoformed plate B	187	-
	Cutter	Anthropomorph	0.0116	*Final Product*	*71.6*	115.4

Results

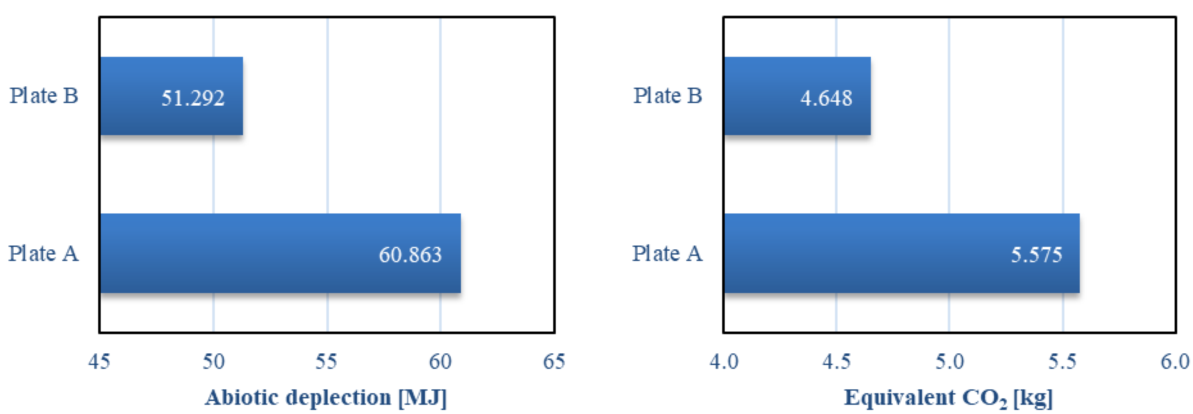
The results are presented in a comparable way to understand the difference between the production of the same component using the initially considered plate dimensions (Plate A) and the minimized ones (Plate B). Starting with the global warming potential the network for the 2 cases is presented in Fig.4. In both cases, the impregnation and thermoforming processes contribute the most while the avoided impacts (green part of the network) are related to the recycle of the waste. Moreover, since the 2 roots for producing the product start from the same impregnation method, their differences mostly rely on the plate dimensions and the related energy for heating them up, prior to the thermoforming process.



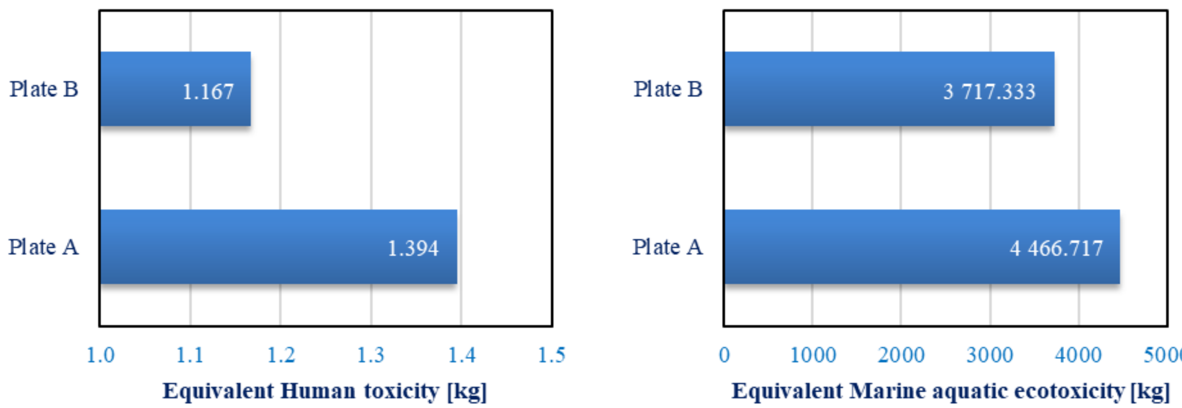
(a) (b)

Figure 4: Network of the global warming potential (GWP) related to the manufacturing of Plate A (a) and B(b) using the IPCC GWP100a method.

In addition, the main environmental impacts for the 2 cases are presented in Fig.5. Since 6 products may be extracted from the initial composite lamina instead of 5, the reduction of the dimensions of the plates prior to the thermoforming process appears to significantly reduce the impacts related to the fossil fuel consumption (Fig.5a), the equivalent CO_2 emitted (Fig.5b) as well as both the human and aquatic toxicities (Fig.5c and 5d).



(a) (b)



(c) (d)

Figure 5: Quantitative results of the most relevant impacts related to the abiotic deplection (fossil fuels) (a) and the equivalent CO2 emissions (b), human toxicity (c) and marine aquatic ecotoxicity (d) by the production of the thermoplastic composite component with the 2 plate scenarios.

Having taken into consideration the characteristics of the processes chain, the additional 1 plate derived from the impregnated lamina is the main factor responsible for the reduction of the environmental impacts. Therefore, considering the fact that a significant part of the thermal-mechanical processes work under quasi-isothermal conditions, the reduction of the dimensions and the waste of a single plate before the thermoforming process does not affect significantly the energy required. As shown in figure 6 all the impact categories result lower for plate B compared to plate A and this was expected as, starting from the initial lamina, the impacts are allocated to 6 plates type B and to 5 plates type A.

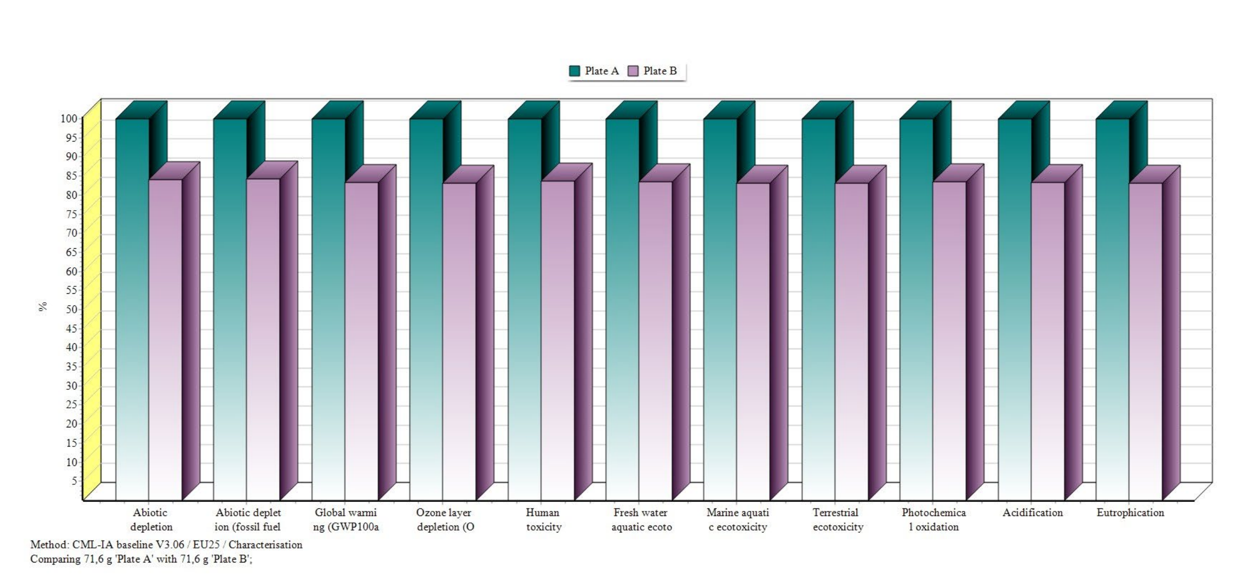


Figure 6. Comparative results with CML-IA baseline method.

Summary and Conclusions

In the present work, a methodology containing a synergy between finite element modelling, manufacturing and life cycle assessment was presented and was applied to a complex mono-layer PP/Woven Textile automotive component. The optimal material temperature was defined by the

FE simulation. In addition, the reduction of the semifinished composite plate dimensions, cut from a previously impregnated lamina were considered. Using a virtual trial-and-error analysis, a reduction to the composite plate dimensions (from 0.8 x 0.52 to 0.6 x 0.43 [m]) was achieved having similar the length-to-width (L/w) ratios (1.54 for Plate A, 1.40 for Plate B).
From the LCA the following conclusions may be extracted:

- The thermomechanical processes occupy a major part of the environmental impact due to the significant energy required for the impregnation and the thermoforming of the composite material.
- Even though the recyclability of the waste produced by the process chain was considered, the positive impact appears to be significantly lower since the material is recycled and not re-used as is.
- The reduction of the dimensions of the composite plate increased the products per lamina by 1. This fact is the main reason behind the decrease of the environmental impact related to the production using the Plate B compared to Plate A.

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