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INVENTORY ANALYSIS OF THE CARBON FIBRES REINFORCED POLYPHENYLENE SULFIDE THERMO-STAMPING MANUFACTURING PROCESS

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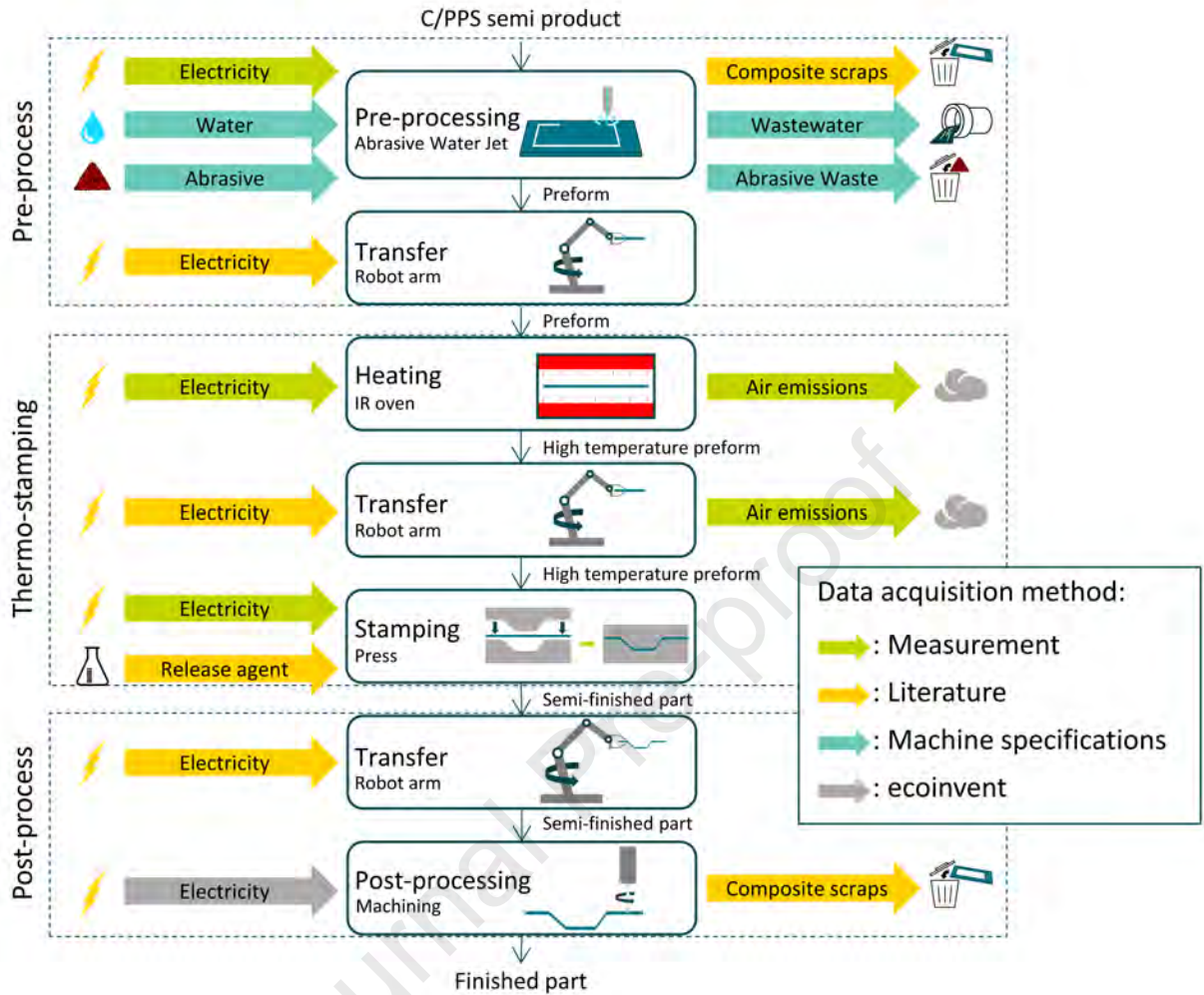
Journal Pre-proof

Abstract:

In the context of environmental transition, the environmental impact of composite parts manufacturing has to be improved as well as the impact of each step of the life cycle. However, a lack of data makes this improvement difficult as few studies have focused on the environmental impact of the manufacturing process of composite parts by giving detailed inventory data and an associated environmental assessment. Thus, this paper aims to propose a comprehensive gate-to-gate environmental analysis of a manufacturing process used in the aerospace industry: the thermo-stamping of carbon fibre reinforced polyphenylene sulfide (C/PPS) composite parts. A methodology based on the life cycle assessment framework is used to quantify and analyse the environmental impact of thermo-stamping parts. First, a complete description of the manufacturing process is proposed to define the studied system boundaries. The manufacturing process is divided into unit processes representing each step of production. Linked to this description, a balance of all the consumptions and waste of materials and energy (inventory flows) is established for each unit process. As a result of the study, each inventory flow is then modelled as a function of the process parameters using data collected from laboratory-scale experimental measurements, databases, and literature. These inventory data models allow computing inventory data of different manufacturing scenarios and C/PPS composite parts. Furthermore, the gate-to-gate environmental assessment of a case study part is presented using the models developed in this paper. C/PPS over-consumption and energy consumed during heating and stamping were identified as unit processes and inventory flows contributing most to the environmental impact of part manufacturing.

Keywords:

Environmental impact; composite polymer processing; inventory data modelling; life cycle assessment



Notations:

C_i : Consumption or emission factor of inventory flow i	R_i : Scraps rate of i
D_i : Flow rate of inventory flow i	S_{mould} : Mould surface
E_i : Electrical energy consumption of i	$T_{0 \text{ part}}$: Initial temperature of the part before IR heating
$H_{\text{parameter}}$: IR oven heating power parameter	T_{emission} : Temperature threshold indicating the start of C/PPS air emissions
$L_{\text{AWJ cut}}$: AWJ cut length	t_i : Duration of the state i
m_i : mass of flow i	$T_{\text{IR setpoint}}$: IR heating setpoint temperature
$M_{\text{C/PPS}}$: C/PPS material density	$v_{\text{IR heating}}$: The heating rate at part surface during IR heating
N_{part} : Number of manufactured parts in the press during one production round	V_i : Volume of flow i
P_i : Electrical power consumption of i	

1. Introduction

Reducing environmental impact is a growing concern in the aerospace industry to achieve one of the Sustainability Development Goals agreed by all members of the United Nations (UN, 2015). For this purpose, European Union has set targets to reduce the environmental impact of aircraft, requiring by 2050 a 75 % decrease in CO₂ emissions per passenger per km (European Commission, 2011). Very recently, states members of the International Civil Aviation Organization, the United Nations specialized agency, have agreed with a more ambitious target. As a result, a long term global aspirational goal was set to net-zero carbon emission of international aviation by 2050 (ICAO, 2022). In this respect, polymer composites have long been identified as a potential solution to reduce the environmental impact of the aeronautic sector, apart from potential rebound effects. Thanks to their good strength-to-weight ratio compared to traditional materials such as metals, the use of these materials allows the weight of structural parts to be reduced. Weight reduction leads to a reduction in fuel consumption, which decreases the environmental impact of aircraft parts throughout their life cycle (Duflou et al., 2012). Fuel consumption reduction during the use phase balances the additional environmental impact of the fibres and matrix production (Timmis et al., 2015) as the use phase contributes to most environmental impact along aircraft parts' complete life cycle (Vidal et al., 2018). However, this improvement is not completely satisfactory because environmental impact is a subject needing continual improvement. Indeed, work will always remain to be made and each actor in the life cycle of aeronautic parts (designers, manufacturers, suppliers ...) has to keep improving its environmental impact. In this paper, we decided to focus on the manufacturing step by proposing an environmental impact assessment of the carbon fibres reinforced polyphenylene sulfide (C/PPS) thermo-stamping process. This process was chosen as it is already used in the aeronautic industry to produce aircraft parts such as reinforcement ribs and fuselage clips (Offringa, 1996). Furthermore, studying thermoplastic composite materials was motivated by the willingness in the aerospace industry to increase the use of these materials because of their higher recyclability, reparability and weldability potential compared to thermoset composites (Zeyrek et al., 2022). Indeed, the recycling of polymer composites is an active research topic that leads to the development of various techniques. The use of thermoplastic allows to develop mechanical recycling processes: the initial material is shredded into smaller parts and reconsolidated under heat and pressure. It produces a recycled material that could lead to lower mechanical properties due to reduced fibre length. Based on the melting ability of the matrix, these processes are able to recycle both the fibres and the matrix unlike other recycling techniques initially developed for thermosets (Bernatas et al., 2021). In this paper, recycling was not studied and only virgin material was used. The aim of this paper is then to provide an inventory analyse (focusing on methodology and data) of C/PPS thermo-stamping, including pre-processing and post-processing. This work is motivated by the need for environmental data to assess the environmental impact of the selected manufacturing process, considering the

environmental assessment as the first step to improve the process from an environmental perspective.

After a short introduction of the context, the second section gives an overview of the state of the art of environmental analysis of composite manufacturing processes and develops the goals of the study. The third section presents the methodology used in this paper for the environmental analysis of the C/PPS thermo-stamping process. Then, complete inventory analysis and relative inventory flow models are shown in the fourth section. After that, the fifth section proposes a case study using the inventory models to assess the environmental impact of a particular part. Finally, sections six and seven show the discussion and conclusion of this paper.

2. State of the art and goals of the study

2.1. Composite manufacturing processes comparisons

In the literature, several studies compared composite manufacturing processes from an environmental point of view. In 2005, Suzuki and Takahashi proposed a comparison between carbon fibre reinforced composite manufacturing processes used in the automotive industry (Suzuki and Takahashi, 2005). Energy intensity data were proposed to express the environmental impact of processes such as hand lay-up, spray-up, resin transfer moulding (RTM) and sheet moulding compound (SMC). These global data represent the needed energy to manufacture 1 kg of material.

Process comparison studies often focused on thermoset composite manufacturing processes, mainly comparing autoclave and out-of-autoclave processes in making parts life cycle assessments. Using data from the literature,ecoinvent v2.1 database, and electrical measurements, Witik et al. (2012) compared the autoclave process with thermal and microwave ovens for curing prepreg or resin infused non-crimp-fabric. They concluded that the environmental impact of producing an aircraft panel in epoxy reinforced with carbon fibre (CF/epoxy) is lower for out-of-autoclave processes. Using global environmental data from the literature, Loukopoulos et al. (2019) had a similar conclusion that out-of-autoclave processes have lower environmental impacts than RTM to produce a CF/epoxy helicopter canopy. Pressure bag moulding was also compared to autoclave processes in the literature. Studying a rear diffuser of a luxury car and a car hood made in CF/epoxy, Vita et al. (2019) and Forcellese et al. (2021, 2020) have shown that this process does not exhibit a lower environmental impact. The authors used data from the literature, ecoinvent database, and experimental measurement to demonstrate this.

In some studies, the environmental impact of thermoplastic composite manufacturing processes was also compared with other processes. Studying a helicopter canopy made in CF/PEEK or CF/epoxy in a cradle-to-gate LCA, Katsiropoulos et al. (2019) compared several manufacturing strategies: RTM, autoclave, and cold diaphragm forming. In their study, only energy consumption was considered and computed using energy intensity data at the process scale from the literature. The authors concluded that the CF/epoxy RTM process has the lowest environmental impact. In another paper, Katsiropoulos and Pantelakis (2020) compared the environmental impact of automated tape placement of CF/PEEK to CF/epoxy autoclave curing for manufacturing a Boeing 747 fuselage panel. In their paper, the environmental assessment was also based on energy consumption computed with global energy intensity data from the literature. The computed environmental results showed the lower environmental impact of the automated tape placement strategy. Recently, Wegmann et al. (2022) published a cradle-to-grave LCA of a car bonnet comparing seven manufacturing scenarios of materials and processes. Metallic processes (aluminium and steel stamping), thermoset processes (RTM with CF or glass fibres) and thermoplastic processes (RTM and thermo-stamping) have been

studied using inventory data from ecoinvent v3.1, calculation and experimental measurement. The authors have shown that the thermo-stamping strategy minimizes environmental impacts.

To sum up, the environmental impact of several composite manufacturing processes has been compared in the literature. These comparisons are helpful for manufacturing process selection. However, environmental impact has mainly been assessed at the process scale that is too global to identify the environmental hotspots of manufacturing processes that manufacturers could set as priorities to improve the process environmental impact. Moreover, the results of the previously reviewed studies are strongly linked to the studied part and the related assumption. Thus, it makes it difficult to generalize the manufacturing processes' environmental results to other similar processes or other parts.

2.2. Study of a single manufacturing process

In the literature, papers have also studied the environmental impact of specific manufacturing processes without making a comparison with other processes. Studying an aircraft wing rib, Al-Lami et al. (2018) studied the environmental impact of an infusion process with autoclave curing of CF/epoxy composite through cradle-to-gate LCA. The authors used a detailed description of the process in several sub-processes and inventory data from German laboratories databases and manufacturers to find process environmental hotspots. Besides, Brecher et al. (2016) worked on automated tape placement to evaluate different production strategies from an environmental, economic and technical point of view. In their paper, an environmental assessment was based on energy consumption measured on a laboratory scale. Using an adapted LCA methodology they have developed (Lindner and Schmitt, 2015), the authors assessed the environmental impact of different manufacturing strategies. The authors investigated the influence of production rate on the environmental impact and the part quality. Identifying that high tape placement speeds perform lower environmental impact but lower quality, the authors proposed adding an extra thermoforming step to compensate for the decrease in consolidation quality. Focusing on another manufacturing process, Alemam and Li (2016) proposed a methodology to improve the diaphragm forming process with environmental indicators also based on process energy consumption. This methodology was developed to help in choosing technologies during the process design. Besides, Müller et al. (2019) worked on the life cycle inventory of a manufacturing process specific to an automotive part made in PA6 reinforced with glass fibres (GF/PA6) with a gate-to-gate approach. The authors proposed a focus on energy consumption to assess the environmental impact. Thus, they measured energy consumption during an infrared heating step for different sets of parameters, showing a significant influence of the process parameters on the energy consumption.

Finally, few studies performed an environmental analysis of a single composite manufacturing process. These studies mainly concentrate on the energy consumption of manufacturing. Besides, some papers showed the influence of the process parameters on energy consumption during the process. Thus, process parameters should influence the process's environmental impact. However, most environmental assessments proposed in the literature do not consider it.

2.3. Environmental assessment of the thermo-stamping process

To the best of our knowledge, only one paper has worked on thermo-stamping environmental impact in terms of inventory data and associated environmental assessments. In a recent comparison of seven manufacturing processes, Wegmann et al. (2022) undertook an environmental assessment of a glass fibre reinforced polycarbonate car bonnet manufactured by thermo-stamping. The assessment was performed with a cradle-to-grave approach, leading to a global vision of the

manufacturing process with few details, as one step among the other lifecycle steps. The authors used generic inventory data yielded by thermodynamic calculations and picked from the ecoinvent v3.1 database. Their environmental assessment of the manufacturing step was energy-oriented and did not include other inventory flows.

2.4. Goals of the study

Thanks to the literature analysis, there seems to be a lack of comprehensive and detailed environmental data on composite manufacturing processes. Available environmental data for composite manufacturing processes are often too generic to analyse the environmental impact at the sub-process scale and identify environmental hotspots. Assumptions such as the selected part, process parameters or materials influence the inventory flow values and, consequently, the environmental impact of the manufacturing process. Moreover, the influence of the process settings is mostly not considered. Thus, generalization of the existing manufacturing processes' environmental results is impossible.

In this paper, we decided to focus on the thermo-stamping process, which has been barely studied from an environmental point of view whereas it is an operational process that is already used in the aerospace industry. The goal of this study is to propose a gate-to-gate environmental analysis of C/PPS part thermo-stamping through:

- A complete description of the thermo-stamping process with the considered inventory flows;
- Models quantifying the listed inventory flows as functions of the process parameters;
- An application of the developed models through a case study that identifies some environmental hotspots.

3. Methodology for the environmental analysis of the C/PPS thermo-stamping process

This paper is based on the Life Cycle Assessment (LCA) framework. LCA is the 4-stages standardized methodology (ISO 14040, 2006) for global environmental analysis from cradle-to-grave: goal and scope definition, inventory analysis, impact assessment and interpretation. This study is carried out in a gate-to-gate scope.

3.1. Scope of the study

The material used in this study is semi-crystalline C/PPS (Toray Cetex® TC 1100) in the form of consolidated laminates of 14 plies and 4.34 mm thick. It is a material used in the industry to produce aircraft parts using thermo-stamping.

The process is decomposed into unit processes as recommended by the Unit Process Life Cycle Inventory (UPLCI) framework (Kellens et al., 2012). Pre-process preform cutting and post-process finishing steps were included in the scope to consider the whole process, which produces finished parts from raw semi-product. The thermo-stamping process can be divided into three main successive steps. The first one is infrared (IR) heating of the composite materials to the manufacturing temperature, higher than the matrix melting temperature. Then, the molten composite sheet is quickly transferred to the press, where the molten material is formed under pressure in a heated mould. Several other steps such as part transfers along the process and mould preparation were also integrated into the studied process. However, the scope of the study does not include steps of material moisture release in a drying oven before manufacturing. Indeed, this step was considered as a material storage step and not as a proper step of the manufacturing process.

Technological choices for the different unit processes were based on observations and interviews at the production site in Nantes of the aerospace supplier and aircraft manufacturer DAHER (France). In this paper, laboratory-scale machines were used. Thus, the results provided in this paper have to be compared with cautions to industrial manufacturing processes operating with machines at much larger scales. The preform heating was performed using a SOPARA Infra-Red (IR) composite oven. This oven can be parametrized by setting heating power with the $H_{\text{parameter}}$ (% of the maximal power of the radiant) and desired temperature $T_{\text{IR setpoint}}$. Two pyrometers measuring temperature on the top and bottom surfaces of the heated part pilot the oven. Besides, a 75T SCAMEX press has been used for the stamping step. This press was composed of a thermal (heating plates) and a mechanical (pressing system) sub-system. Press parameters were the temperature of the plates and the closing force. The process also included an OMAX ProtoMAX Abrasive Waterjet (AWJ) preform cutting, robot arm handling and machining post-processing. Thanks to the proposed process description, all the consumption and waste of materials and energy (named inventory flows) were listed for each unit process. Figure 1 describes the process linked to the different inventory flows considered in the environmental analysis. In this paper, equipment was excluded from the gate-to-gate study boundaries. C/PPS semi-product consumption was considered and divided into two categories, as shown in Figure 1. First, a fraction of the consumed material finishes in the produced part and only relies on the part geometry. On the other hand, a second fraction of the material consumed ends up as waste. This amount of material, which we will call material overconsumption, partly relies on the process settings.

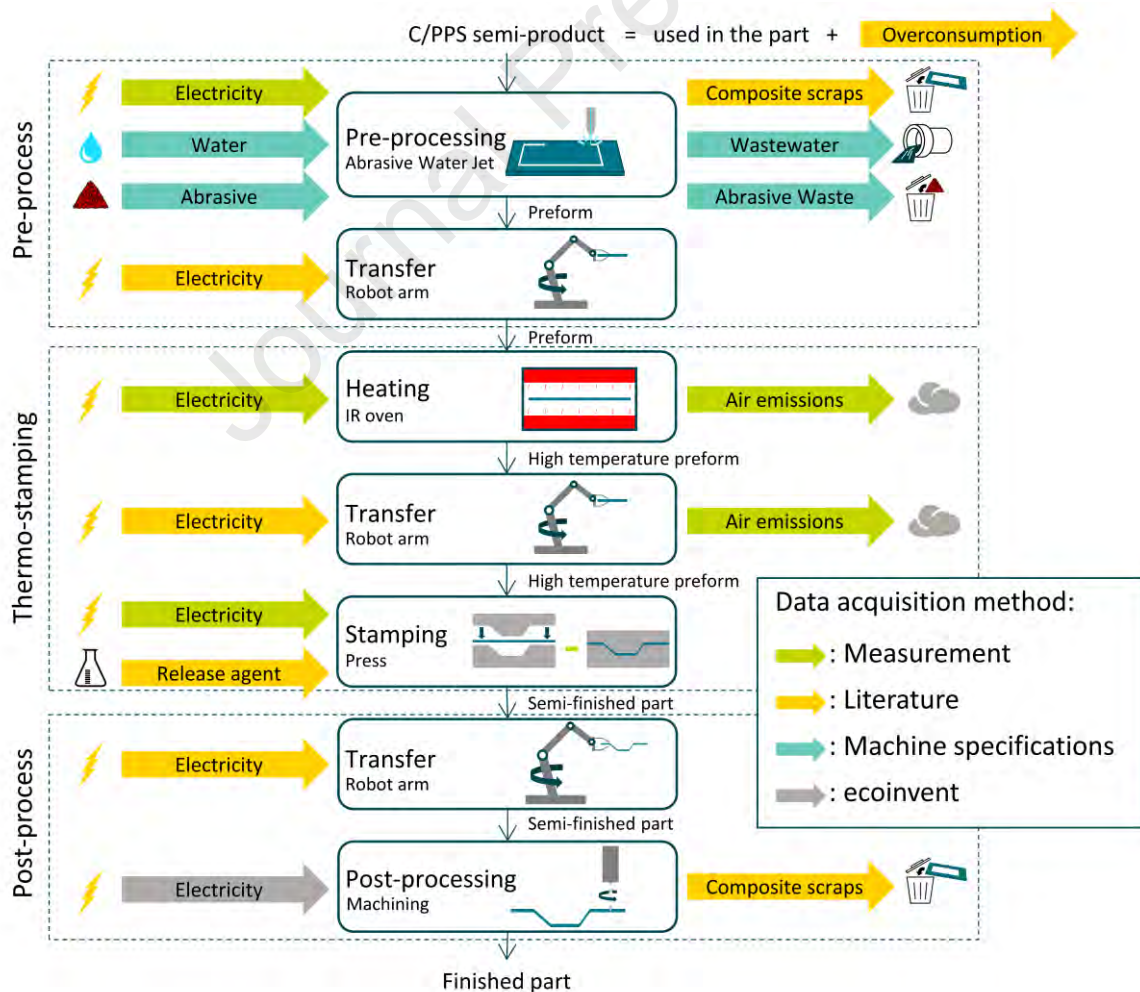


Figure 1: Process tree of the studied thermo-stamping process.

Several outgoing inventory flows have been identified in the process description and can be handled in the industry through different scenarios. As mentioned in the introduction, recycling can be chosen for the end of life of C/PPS scraps to produce a material that can be used for less structural applications. Water used during the AWJ process can also be recycled using filtering techniques. This scenario could decrease the amount of water consumed during AWJ processing. On the other hand, abrasives used during the AWJ process cannot be recycled. This is because the grains are polished during the process, making them less abrasive and therefore ineffective for further cutting.

In thermo-stamping, the three main steps (heating, transfer and stamping) are correlated and linked to the thermal evolution of the material during manufacturing. For example, the heating temperature of the IR oven and the transfer duration influence the stamping temperature of the material. As the parts' quality depends on the material thermal history, it is essential to consider the relations between the process steps. In this respect, process parameters must be kept within intervals to produce parts with the required quality. This paper uses the process parameters values for thermo-stamping C/PPS from the literature and the manufacturer expertise exposed in Table 1. In this paper, we assumed that air emissions from release agent were negligible because only a small amount of this agent is applied on the mould at relatively low temperature.

Table 1: Process parameters for thermo-stamping C/PPS used in this study.

Heating temperature	310 °C-370 °C	Abbassi et al. (2011); Han et al. (2015); Jamin et al. (2016); Joppich et al. (2016); McCool et al. (2012)
Mould temperature	50 °C-230 °C	Abbassi et al. (2011); Han et al. (2015); Jamin et al. (2016); Joppich et al. (2016); McCool et al. (2012)
Stamping force	2.2 MPa - 6 MPa	Jamin et al. (2016); Joppich et al. (2016)
Heating step	Around 90 s max.	Manufacturer expertise
Transfer step	Around 5 s	Manufacturer expertise

To develop the inventory analysis, the functional unit was defined as the manufacturing of one part by this thermo-stamping process with process parameters within the range previously identified. To assess the inventory, the mould used in the press was designed to produce plates. The width and length of the plates produced were considered as parameters of the inventory flow models developed. Maximum dimensions of the part produced with the studied process are 300 mm x 300 mm x 4.34 mm corresponding to a weight of 0.59 kg.

3.2. Inventory data collection and modelling

Based on the process description, inventory data were quantified and modelled as functions of process parameters. Inventory data were collected from experimental measurements, machine specifications, literature and the ecoinvent v3.5 database. In Figure 1, the origins of the data for each inventory flow are colour-coded.

3.2.1. Electrical energy measurement

To build energy consumption models as functions of the machine parameters, the methodology is divided into three steps, as exposed in Figure 2. After measuring the electrical power consumption of the machines with different settings, a layout of the power profile of the machine is proposed. This layout is based on the electrical measurement shape and the machine states temporal decomposition. A constant piecewise function was chosen for its good fit with the shape of most of

the power measurements and its simplicity of modelling. Then, the power profile model coefficients (P_i in Figure 2) are quantified using the power consumption records for each setting. As an optional third step, the power profile model coefficients are expressed as functions of the machine settings.

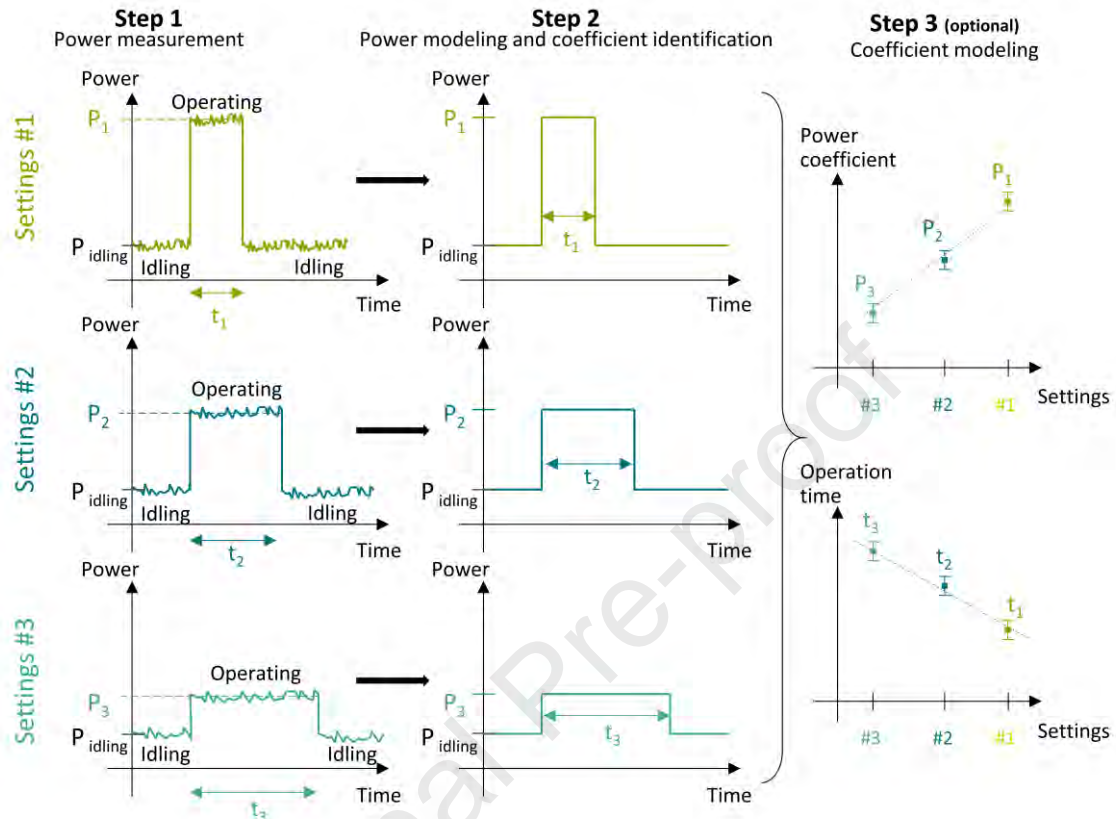


Figure 2: Illustration of the electrical energy consumption modelling methodology.

Fluke 434 II with Fluke i30s current clamps were used to measure the active power consumed by the IR oven, the press and the AWJ machine using settings presented in Table 2. Those settings were chosen to fulfil the process parameters used in this study (Table 2). For the IR oven, tests were carried out using three heating power and three temperature settings. The minimum heating power tested was chosen with respect to the 90 s duration limit of the heating.

Table 2: Machine settings used during electrical power consumption measurements.

Machine	Parameters	Power measurement strategy	
AWJ machine	Cutting speed: 4 mm/s	Measurement at the power supply	
		Power computed using an average current value of 230V	
IR oven	Heating power	Measurement : • at the power supply • at a sub-system composed of two radiant heaters	
	70 %		310 °C
			370 °C
	85 %		310 °C
			335 °C
	100 %		335 °C
370 °C			
Press	Plate temperature: 100 °C	Measurement at the power supply	

Closing force: 200 kN

3.2.2. Air emissions measurement

As the thermo-stamping process heats thermoplastic materials to high temperatures to soften the polymer matrix, emissions to air may result from material degradation and material additive vaporization mechanisms (Patel and Xanthos, 2001). Two types of emissions may occur: particulate matter (PM) and gaseous compounds such as volatile organic compounds (VOCs). According to the literature, the gases emitted during PPS heating are mainly hydrogen sulfide (H₂S) and benzenethiol (Zuo et al., 2019). Experimental measurements were developed to collect inventory data for this elementary flow using the measuring equipment shown in Figure 3-d. A Q-Trak (TSI) indoor air quality monitor with a 987 VOC probe capable of detecting H₂S and benzenethiol was used to measure gaseous compound emissions. A DUSTTRAK (TSI) was also used to detect 0.1-10 μm PM emissions. Measurements with both instruments were performed using three experimental setups described in Figure 3. Emissions have been measured:

- At the output of the IR oven exhaust system during C/PPS heating tests (Figure 3 – a.);
- On top of a confined heating plate used to heat C/PPS (Figure 3 – b.);
- At the exhaust system of a non-ventilated calcining furnace (Figure 3 – c.).

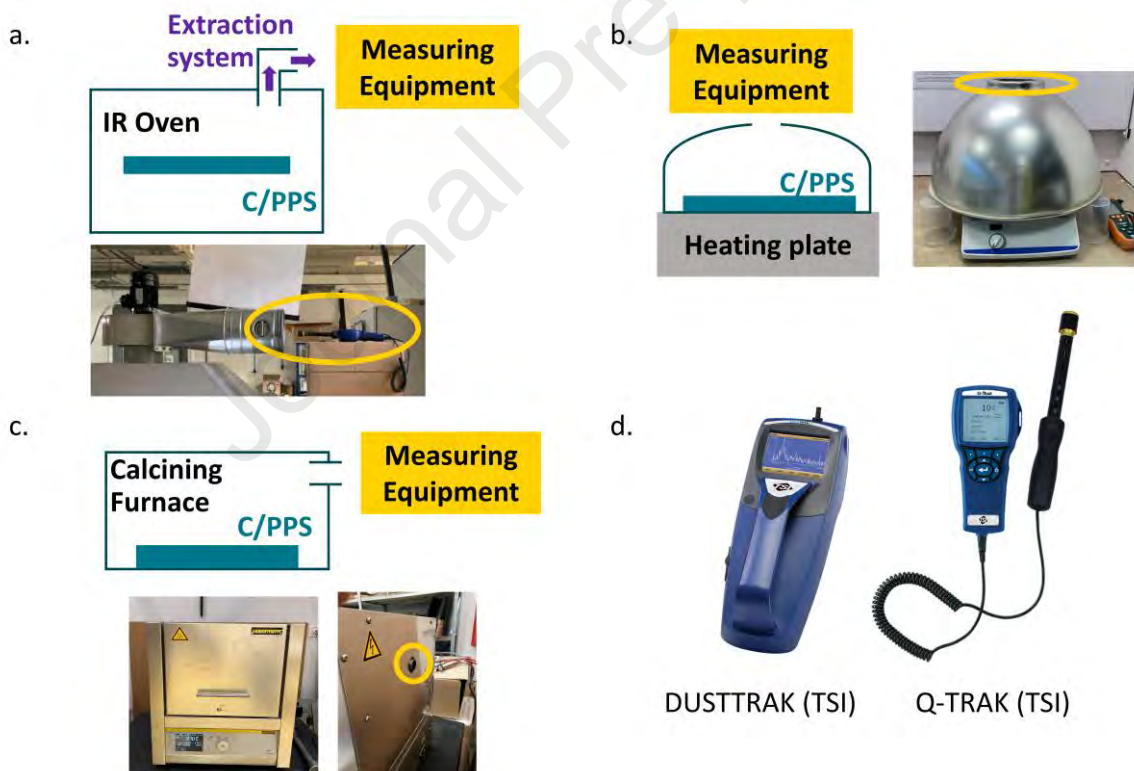


Figure 3: Air emissions experimental measurement setups and measuring equipment.

As thermoplastic emissions increase with the temperature (Yamashita et al., 2009), the temperature of the different tests was set to the maximum used for C/PPS thermo-stamping (370 °C) to maximize emissions during the tests.

4. Inventory analysis results

4.1. C/PPS use

The mass of C/PPS used in the process can be defined as the sum of the mass of the part and the mass of overconsumed material. The mass of the part can be easily estimated, knowing the part geometry. However, overconsumption of C/PPS can be difficult to assess because factors such as the part geometry, the blank holder system employed, and the initial geometry of the composite blank must be considered. Thus, the use of a time consuming approach such as simulation or experimental measurements is necessary for each geometry to evaluate C/PPS overconsumption accurately. In this paper, another strategy has been chosen: a generic model of the C/PPS scrap rate based on literature data is proposed. Despite the lack of accuracy of this strategy, the strength of this approach is its ability to quickly estimate the material overconsumption knowing the mass of the part produced. The total scrap rate ($R_{total\ scraps}$) has been computed as the mean value of composite manufacturing process scrap rates found in the literature and exposed in Table 3. As a result, a 34 % scrap rate was calculated, consistent with the manufacturer's estimations.

Table 3: Composite scrap rates found in the literature.

Reference	Composite manufacturing process	Scraps rate
Loukopoulos et al. (2019)	RTM and autoclave processing	80 %
Dér et al. (2022)	SMC	60 %
Witik et al. (2012)	Prepreg and liquid infused resin fabric cured with : <ul style="list-style-type: none"> • Autoclave • Thermal oven • Microwave oven 	30 %
Al-Lami et al. (2018)	Liquid infused resin fabric cured with microwave oven	50 %
Mativenga et al. (2017)	No specific process: Average values based on manufacturers' responses to a survey in South Africa (SA) and the United Kingdom (UK)	5.7 % in SA 11.3 % in the UK
Rybicka et al. (2015)	Automated Tape Lay-up cured with an autoclave (aerospace industry)	27 %
La Rosa et al. (2014)	Resin infusion	20 %
Vita et al. (2019)	Autoclave processing and Pressure Bag Moulding	20 %
Zhang et al. (2020)	No specific process	40 %
Mean value		34 %

4.2. Pre-processing: preform abrasive water jet cutting

The energy consumption model of the AWJ machine was based on experimental measurement. The model was divided into two machine states: cutting and idling. Models for water and abrasive consumption were developed from the machine specifications. Wastewater and abrasive waste were supposed equal water and abrasive input. Then, AWJ scraps were assessed as a fraction of the total scraps, using an arbitrarily set AWJ scraps rate ($R_{AWJ\ scraps}$).

4.3. Infra-red heating

The IR oven electrical energy consumption model was developed using experimental electrical measurement. Three machine states were identified. A first state was defined as the heating of the part surface to the setpoint temperature. Then, a maintaining phase homogenizes temperature in the part thickness. This state is a regulation state where the oven maintains the setpoint temperature. Idling has been identified as the last state of the oven. In the proposed model, electrical energy to maintain the temperature was chosen as the energy measured to keep a part at 370 °C with maximum heating power ($H_{parameter} = 100\%$) for 30 seconds. Figure 4 shows the proposed model with the maintaining energy represented by the blue area.

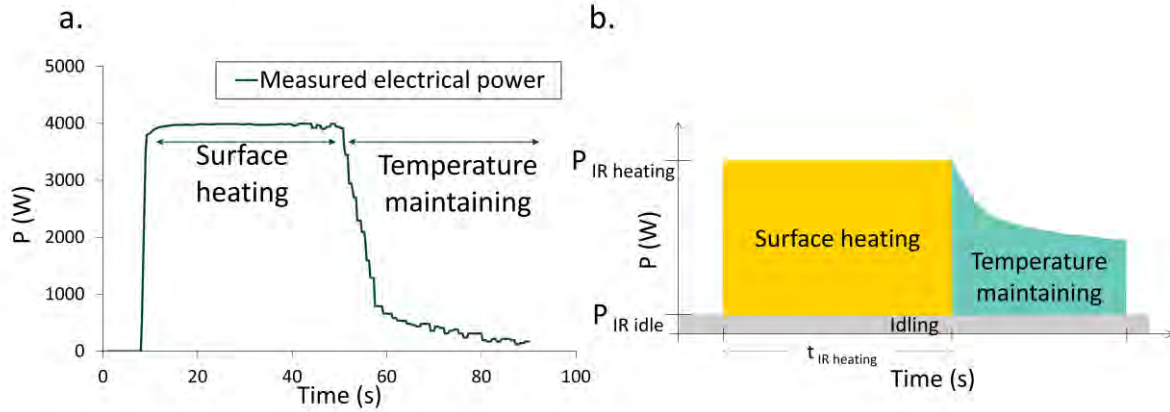


Figure 4: a. Example of electrical power measured at a sub-system composed of two radiant heaters ($H_{\text{parameter}} = 100\%$ and $T_{\text{setpoint}} = 370\text{ }^{\circ}\text{C}$). b. Proposed electrical power model.

Besides the electrical model, the temperature at the surface of the part was modelled using the temperature data measured by the IR oven pyrometers. A heating rate was modelled to compute the duration of the heating phase in the IR oven, depending on the oven settings. First, linear regression was used to compute heating rates for each tested setting, as shown in Figure 5-a. Then, linear regression was used again to model the heating rate as a function of the IR oven heating power parameter, as shown in Figure 5-b. For each linear regression, the coefficients of determination (R^2) values were found between 0.97 and 1. Several heating cycles were needed during the experiments before reaching a steady state. It can be explained by the need to heat the IR oven frame until it reaches a steady temperature. The model proposed in this paper was developed for IR oven steady state only.

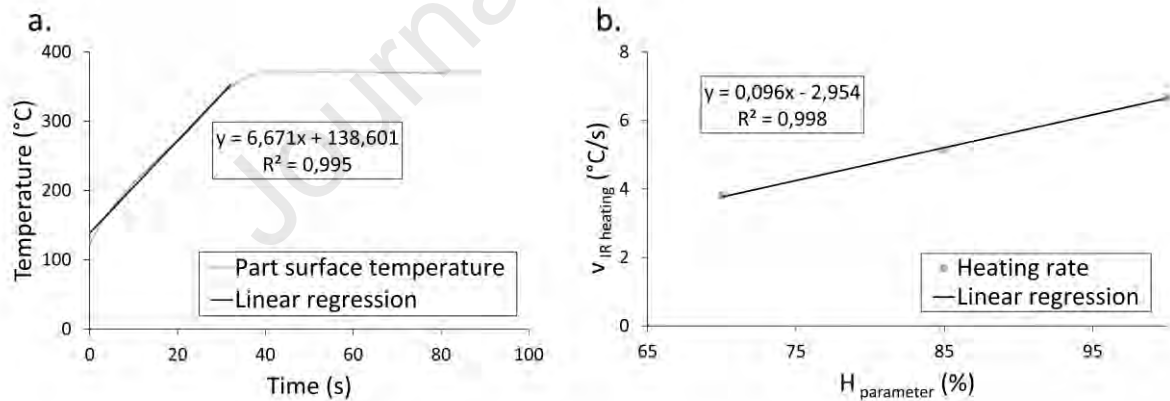


Figure 5: a. Example of heating rate computation based on temperature measurements ($H_{\text{parameter}} = 100\%$; $T_{\text{setpoint}} = 370\text{ }^{\circ}\text{C}$). b. Computed $v_{\text{IR heating}}$ from experimental measurement and modelling as a function of $H_{\text{parameter}}$.

Also based on experimental measurements, PM and gaseous compound emissions models have been developed for the IR heating step. However, measurements did not detect gaseous compounds nor PM emissions. In consequence, emissions were assumed equal to the VOC detector detection threshold and the standard deviation of the PM measurement values. Then, emission factors were computed using these assumptions, exhaust flow rate and C/PPS heated mass data. To overestimate the environmental impact of the air emissions, we chose the worst scenario: hydrogen sulfide (H_2S) as the only emitted gaseous compound and $2.5\text{ }\mu\text{m}$ as the maximum diameter for PM emissions.

4.4. Transfer

The electrical energy consumption model for a Comau SMART SiX robot arm proposed by Chemnitz et al. (2011) was used in this paper because the modelled process fits with thermo-stamping applications. Indeed, the robot arm motion used to develop the model is similar to a pick-place-move safe motion representative of the thermo-stamping process. Moreover, this Comau robot arm payload and reach were adapted to thermo-stamping process applications. During the transfer to the press from the IR oven, air emissions were considered as the material temperature remained high. Emission factors developed for the IR heating step were used to model these emissions.

4.5. Stamping

Electrical consumptions associated with mechanical and thermal systems were modelled separately, using electrical power measurements. Two components were identified for the thermal model, as presented in Figure 6-a. The first component corresponds to the energy needed to heat the system to the setpoint temperature at the production start ($E_{\text{press heating}}$). This energy must be distributed depending on the number of batch parts (N_{part}). The second component represents the energy consumed to maintain the system at the setpoint temperature, modelled by a constant electrical power $P_{\text{press maintain}}$. The mechanical system was modelled by a constant piecewise function with the power parameter $P_{\text{press stamping}}$, as shown in Figure 6-b. In the same way, idling was modelled by a constant idling power $P_{\text{press idle}}$. Finally, Figure 6-c. depicts the overall model obtained by gathering the thermal and mechanical models.

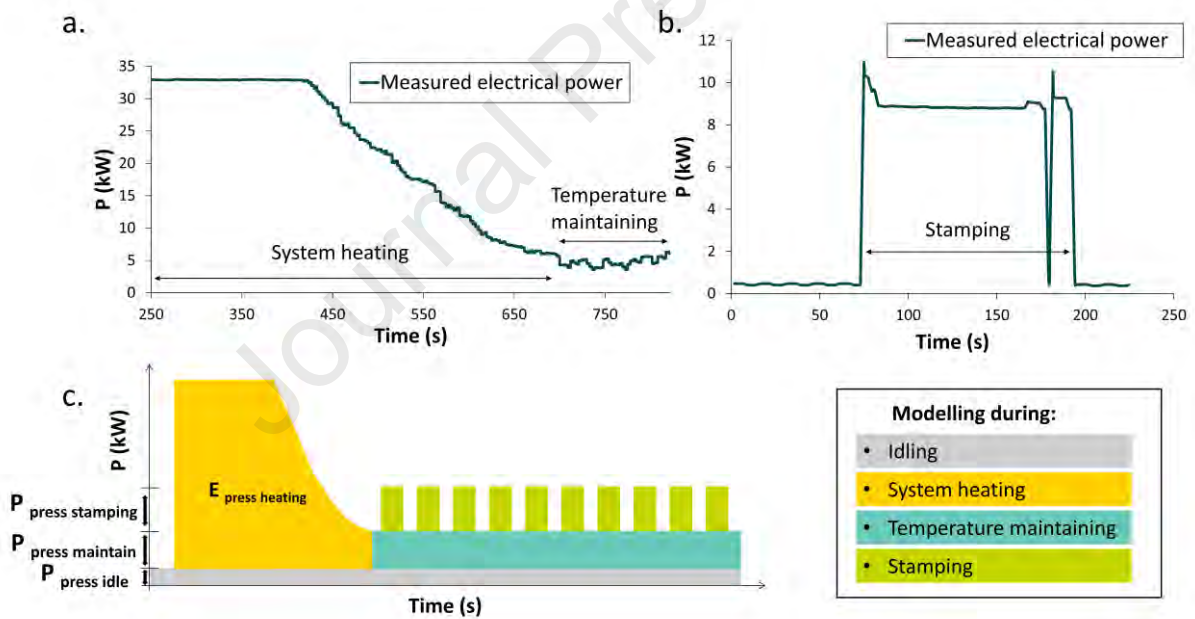


Figure 6: Press electrical power consumption modelling: a. Example of thermal sub-system electrical power measurement. b. Example of mechanical sub-system electrical power measurement. c. Proposed press power consumption modelling for the production of 10 parts.

Besides, mould release agent consumption was modelled using literature data presented in Table 4. Release agent consumption factors were computed using the consumption and part geometry information available in each paper. Finally, the mould release agent consumption factor used in this paper was calculated at $1.17 \text{ E-}02 \text{ kg/m}^2/\text{part}$ as the mean value of literature data.

Table 4: Release agent consumption data extracted from the literature.

Reference	Literature data	Release agent consumption factor
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Forcellese et al. (2021)	0.015 kg consumed for a 1.3 m ² part manufactured by autoclave processing and pressure bag moulding	1.15E-02 kg/m ² /part
Forcellese et al. (2020)	0.03 kg consumed for a 1.8 m ² part manufactured by autoclave processing and pressure bag moulding	1.67E-02 kg/m ² /part
Vita et al. (2019)	0.03 kg consumed for a 3 m ² part manufactured by autoclave processing and pressure bag moulding	1.00E-02 kg/m ² /part
Wegmann et al. (2022)	1 g consumed every 2 000 parts of 1.5 m ² surface manufactured by RTM and stamp-forming	3.33E-04 kg/m ² /part
Hann Chua et al. (2015)	0.4 kg consumed for a 19.9 m ² part manufactured by autoclave processing	2.01E-02 kg/m ² /part
Mean value		1.17 E-02 kg/m²/part

4.6. Post-processing

An energy consumption model for post-process machining was developed using the ecoinvent v3.5 database. Electrical energy consumption was picked from the model for chromium steel milling as no data are available for composite milling in ecoinvent. This model was chosen because of its higher energy consumption than other milling models found in ecoinvent. In line with the AWJ cutting step, scraps were computed using an arbitrary rate complementary to the AWJ rate ($R_{\text{machining scraps}} = 1 - R_{\text{AWJ scraps}}$).

4.7. Overview of the developed models

Table 5 presents the inventory models developed in this paper as functions of process parameters.

Table 5: Inventory flow models proposed for C/PPS thermo-stamping.

Unit process	Parameters	Model	Model coefficients
AWJ preform cutting		$m_{C/PPS} = m_{part} + m_{C/PPS \text{ overconsumption}}$	
		with $m_{part} = M_{C/PPS} * V_{part}$	$M_{C/PPS} = 1\ 550\ \text{kg/m}^3$
	V_{part}	and $m_{C/PPS \text{ overconsumption}} = M_{C/PPS} * V_{part} * R_{total \text{ scraps}}$	$R_{total \text{ scraps}} = 34\ \%$
	$L_{AWJ \text{ cut}}$	$E_{AWJ \text{ cut}} = (P_{AWJ \text{ cut}} / v_{AWJ \text{ cut}}) * L_{AWJ \text{ cut}} + P_{AWJ \text{ idle}} * t_{AWJ \text{ idle}}$	$P_{AWJ \text{ idle}} = 212.7\ \text{W} \pm 8.5\ \text{W}$
	$t_{AWJ \text{ idle}}$	$V_{AWJ \text{ water}} = (D_{AWJ \text{ water}} / v_{AWJ \text{ cut}}) * L_{AWJ \text{ cut}}$	$P_{AWJ \text{ cut}} = 3\ 825\ \text{W} \pm 40\ \text{W}$
	$V_{AWJ \text{ cut}}$	$m_{AWJ \text{ abrasive}} = (D_{AWJ \text{ abrasive}} / v_{AWJ \text{ cut}}) * L_{AWJ \text{ cut}}$	$v_{AWJ \text{ cut}} = 4\ \text{mm/s}$
$R_{AWJ \text{ scraps}}$	$m_{AWJ \text{ scraps}} = M_{C/PPS} * V_{part} * R_{total \text{ scraps}} * R_{AWJ \text{ scraps}}$	$D_{AWJ \text{ water}} = 1.38\text{E-}2\ \text{L/s}$	
		$V_{AWJ \text{ wastewater}} = V_{AWJ \text{ water}}$	$D_{AWJ \text{ abrasive}} = 1.9\text{E-}03\ \text{kg/s}$
		$m_{AWJ \text{ abrasive waste}} = m_{AWJ \text{ abrasive}}$	
IR oven heating	$H_{parameter}$	$E_{IR \text{ oven}} = P_{IR \text{ heating}} * t_{IR \text{ heating}} + E_{IR \text{ maintain}} + P_{IR \text{ idle}} * t_{IR \text{ idle}}$	$V_{IR \text{ heating}} = 0.096 * H_{parameter} - 2.9535$
	$T_{IR \text{ setpoint}}$	with	$P_{IR \text{ idle}} = 296\ \text{W} \pm 10\ \text{W}$
	$T_{0 \text{ part}}$	$t_{IR \text{ heating}} = (T_{IR \text{ setpoint}} - T_{0 \text{ part}}) / v_{IR \text{ heating}}$	$P_{IR \text{ heating}} = 547 * H_{parameter} - 6\ 601$
	$t_{IR \text{ idle}}$	$m_{IR \text{ H2S}} = C_{H2S} * m_{preform} * t_{emission}$	$E_{IR \text{ maintain}} = 444\ 092\ \text{J}$ (30 s at 370 °C and $H_{parameter} = 100\ \%$)
	$m_{preform}$	$m_{IR \text{ PM 2.5}} = C_{PM 2.5} * m_{preform} * t_{emission}$	$C_{H2S} = 27\ \text{mg/kg/s}$
		with $t_{emission} = (T_{IR \text{ setpoint}} - T_{emission}) / v_{IR \text{ heating}} + 30$	$C_{PM 2.5} = 1.55\text{E-}01\ \text{mg/kg/s}$
Robot arm handling	$t_{robot \text{ move}}$	$E_{robot} = E_{robot \text{ move}} + P_{robot \text{ idle}} * t_{robot \text{ idle}}$	$E_{robot \text{ move}} = 1.16 * t_{robot \text{ move}}^2 + 193 * t_{robot \text{ move}} + 1804\ \text{J}$
	$t_{robot \text{ idle}}$	For the transfer to press :	$P_{robot \text{ idle}} = 260\ \text{W}$
		$m_{robot \text{ H2S}} = C_{H2S} * m_{preform} * t_{robot \text{ move}}$	$C_{H2S} = 27\ \text{mg/kg/s}$
		$m_{robot \text{ PM 2.5}} = C_{PM 2.5} * m_{preform} * t_{robot \text{ move}}$	$C_{PM 2.5} = 1.55\text{E-}01\ \text{mg/kg/s}$
Stamp forming	$t_{press \text{ process}}$	$E_{press} = E_{press \text{ thermal}} + E_{press \text{ mechanical}} + P_{press \text{ idle}} * t_{press \text{ process}}$	For mould set at 100 °C and 200 kN closing force
	$t_{press \text{ stamping}}$	$E_{press \text{ thermal}} = E_{press \text{ heating}} / N_{part} + P_{press \text{ maintain}} * t_{press \text{ process}}$	$E_{press \text{ heating}} = 36\ 478\ 448\ \text{J} \pm 77\ 178\ \text{J}$
	N_{part}	$E_{press \text{ mechanical}} = P_{press \text{ stamping}} * t_{press \text{ stamping}}$	$P_{press \text{ maintain}} = 9\ 213\ \text{W} \pm 1\ 124\ \text{W}$
	S_{mould}	$m_{press \text{ release agent}} = S_{mould} * C_{release \text{ agent}}$	$P_{press \text{ idle}} = 427\ \text{W} \pm 23\ \text{W}$
			$P_{press \text{ stamping}} = 8\ 374\ \text{W} \pm 131\ \text{W}$
			$C_{release \text{ agent}} = 1.17\ \text{E-}02\ \text{kg/m}^2$
Machining		$R_{machining \text{ scraps}} = 1 - R_{AWJ \text{ scraps}}$	
		$m_{machining \text{ scraps}} = M_{C/PPS} * V_{part} * R_{global \text{ scraps}} * R_{machining \text{ scraps}}$	$C_{machining \text{ energy}} = 1.15\text{E+}07\ \text{J/kg}$
		$E_{machining} = m_{machining \text{ scraps}} * C_{energy}$	

5. Case study: environmental assessment of thermo-stamping a C/PPS part

5.1. Case study description

In this section, we propose a gate-to-gate assessment to study the manufacturing of a 250 mm x 200 mm x 4.34 mm C/PPS part in France using the thermo-stamping process. Table 6 exposes the manufacturing parameters and model assumptions. In this environmental assessment, the functional unit has been defined as the thermo-stamping of a part in this case study. The objective of this case study is to identify the major causes of environmental impact of the thermo-stamping process which can be seen as a priority action lever for the manufacturer.

Initial blank dimensions were assumed to be 10 mm wider along all edges to take the use of the blank holder into account. Mould surface (S_{mould}) computation was based on the preform shape.

In this paper, the consumption of C/PPS has been divided into two categories: the material that constitutes the part and the overconsumption that ends up as scraps after manufacturing. In this section, only C/PPS overconsumption was considered in the environmental assessment whereas the material of the part was excluded. This is because this quantity is only driven by the part geometry which does not depend on the manufacturing process. As no action on this flow is possible at the manufacturing stage, we decided to remove it from the assessment to keep focusing on the goal of this case study from the manufacturer's perspective. Overall C/PPS material consumption was estimated at 451 g, with 114 g of material overconsumed. Associated scraps were assumed to occur at the pre-processing step mainly.

The batch size and timing of the unit processes were set thanks to industrial observations. The cycle time of press stamping was set equal to the IR heating cycle time to enable the heating and the stamping of two parts simultaneously. Consequently, the idling time of the machine decreased. The idling time of the robot arm was set equal to the heating and stamping time. To overestimate the environmental impact of air emissions, the threshold temperature of emission has been arbitrarily set to the 20°C.

Table 6: Case study thermo-stamping process parameters and computed inventory dataset.

Unit process	Parameters values	Computed inventory data
AWJ preform cutting	$t_{\text{AWJ idle}} = 60$ s	$E_{\text{AWJ cut}} = 912$ kJ
	$L_{\text{AWJ cut}} = 0.94$ m	$V_{\text{AWJ water}} = 3.2$ L
	$R_{\text{AWJ scraps}} = 90$ %	$m_{\text{AWJ abrasive}} = 447$ g
		$m_{\text{AWJ scraps}} = 103$ g
		$V_{\text{AWJ wastewater}} = 3.2$ L
		$m_{\text{AWJ abrasive waste}} = 447$ g
IR oven heating	$H_{\text{parameter}} = 90$ %	$E_{\text{IR oven}} = 3\,070$ kJ
	$T_{0\text{ part}} = 20$ °C	$m_{\text{IR H2S}} = 908$ mg
	$T_{\text{setpoint}} = 370$ °C	$m_{\text{IR PM 2.5}} = 5.2$ mg
	$T_{\text{emission}} = 20$ °C	
	$t_{\text{IR idle}} = 8$ s	
Robot arm handling	$t_{\text{robot move}} = 8$ s	$E_{\text{robot}} = 82$ kJ
	$t_{\text{robot idle}} = 91.5$ s	$m_{\text{robot H2S}} = 79.3$ mg
		$m_{\text{robot PM 2.5}} = 0.455$ mg
Stamp forming	$N_{\text{part}} = 10$ part	$E_{\text{press}} = 5\,374$ kJ
	$t_{\text{process}} = 99.5$ s	$m_{\text{press release agent}} = 1.3$ g
	$t_{\text{stamping}} = 91.5$ s	

	$S_{\text{mould}} = 0.11 \text{ m}^2$	
Machining	$m_{\text{machining scraps}} = 11$	g
	$E_{\text{machining}} = 132$	kJ

After computing the inventory data using the developed models (Table 6), Environmental impact was assessed using SimaPro software with secondary data from the ecoinvent v3.5 database. Impact 2002+ v2.15 method was chosen as it is the same as the one used in the only paper studying the environmental impact of thermo-stamping (Wegmann et al., 2022). Robot handling steps were summed up as a single unit process. Transport steps were excluded and landfilling was chosen as the waste treatment scenario. Polydimethylsiloxane was selected as the mould release agent, in line with Wegmann et al. (2022). To assess the impact of C/PPS overconsumption during the process, we only considered PPS and CF production and not the semi-product manufacturing step. PPS production was modelled using ecoinvent v3.5. We computed the environmental impact of carbon fibre production using the data from Khalil (2017) and Duflou et al. (2009), aggregated by Forcellese et al. (2020). However, variability in environmental data has been reported in the literature for carbon fibre production (Groetsch et al., 2023) and work remains to be done to get the scientific community to agree on a data set. Thus, the confidence in the calculated results can be discussed.

5.2. Environmental analysis results

Environmental impact assessment results are set out in Figure 7. C/PPS material overconsumption was identified as the primary contributor to all the computed environmental impact. Regarding the global warming impact category, 90 % of the computed impact came from the material overconsumption flow. 81 % of this impact was caused by the production of the carbon fibre and 19 % was caused by the production of PPS. The heating and stamp-forming steps also had a significant environmental impact. For the global warming impact indicator, 3 % of the impact was caused by the IR heating and 6 % by the stamp forming steps. The energy consumption flow governs the environmental impact of these two unit processes: the entire environmental impact of the IR heating stage on global warming was caused by the electrical energy consumption and 83 % of the environmental impact of the stamping step was caused by the electrical energy consumption.

Air emissions accounted for three environmental impact indicators: PM_{2.5} emissions contributed to around 0.31 % of the respiratory inorganics environmental impact; H₂S emissions contributed to 0.52 % of non-carcinogens and 14.8 % of aquatic acidification environmental impacts.

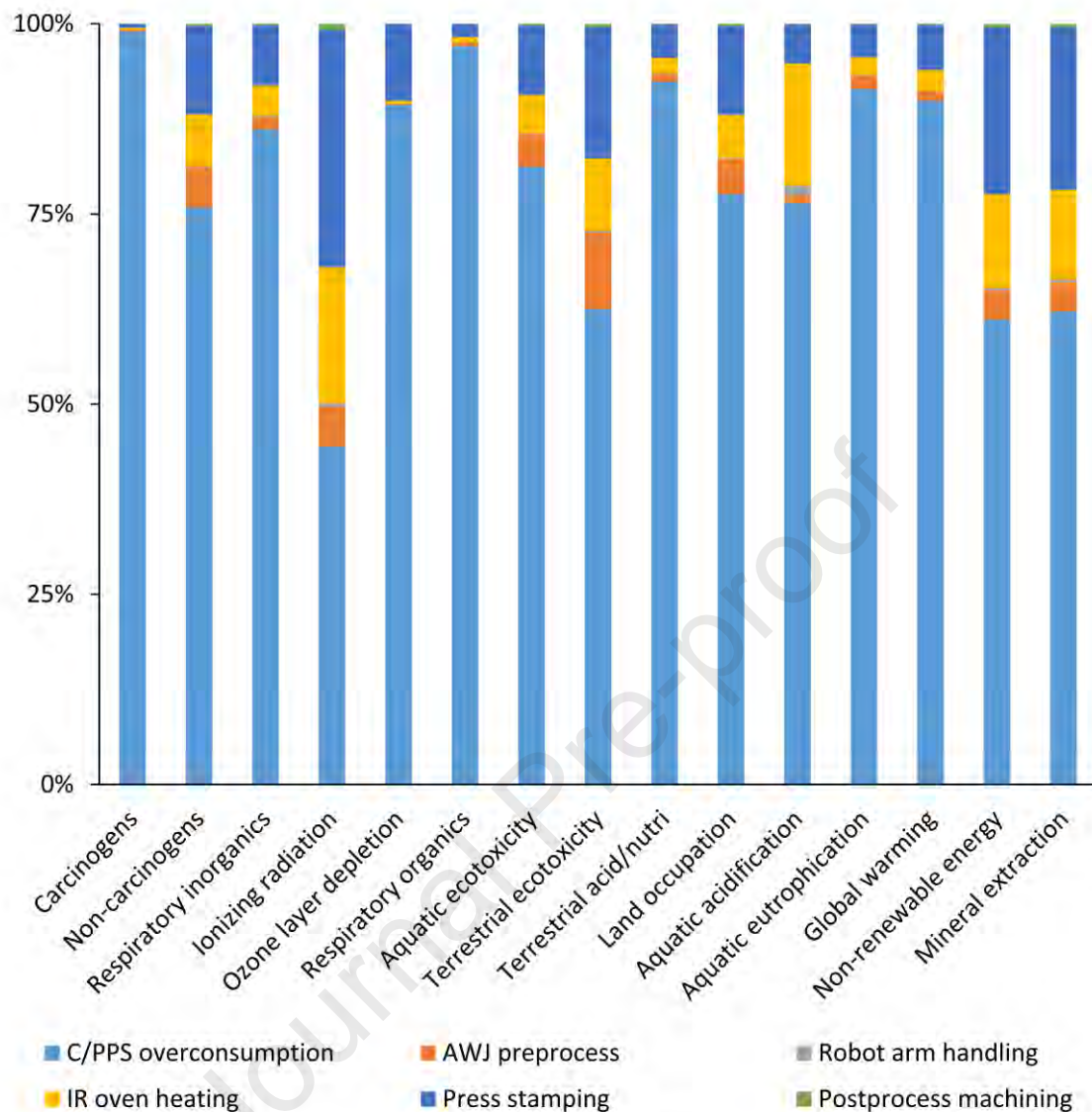


Figure 7: Environmental impact assessment of the case study part manufacturing (Impact 2002+ v2.15).

5.3. Sensitivity analysis

A sensitivity analysis was performed using the case study as a reference case. The four parameters presented in Table 7 are varied one by one to understand their influence on the environmental results.

Table 7: Parameters values for the sensitivity analysis.

Parameters	Parameters values
$H_{\text{parameter}}$	70 % ; 90 %* ; 100 %
$T_{\text{IR heating}}$	310 °C ; 335 °C ; 370 °C*
$R_{\text{AWJ scraps}}$	10 % ; 50 % ; 90 %*
N_{part}	1 ; 10* ; 100

* Reference case parameter values

Results showed that the three main contributors to the process's environmental impact remain the same, regardless of the parameter values: C/PPS overconsumption followed by the stamp forming and IR heating steps. Figure 8 illustrates the sensitivity analysis result for the global warming indicator. The results also show the significant influence of the number N_{part} of part produced. It can be explained by the impact of this parameter on the fraction of the energy needed to heat the mould used for the part production.

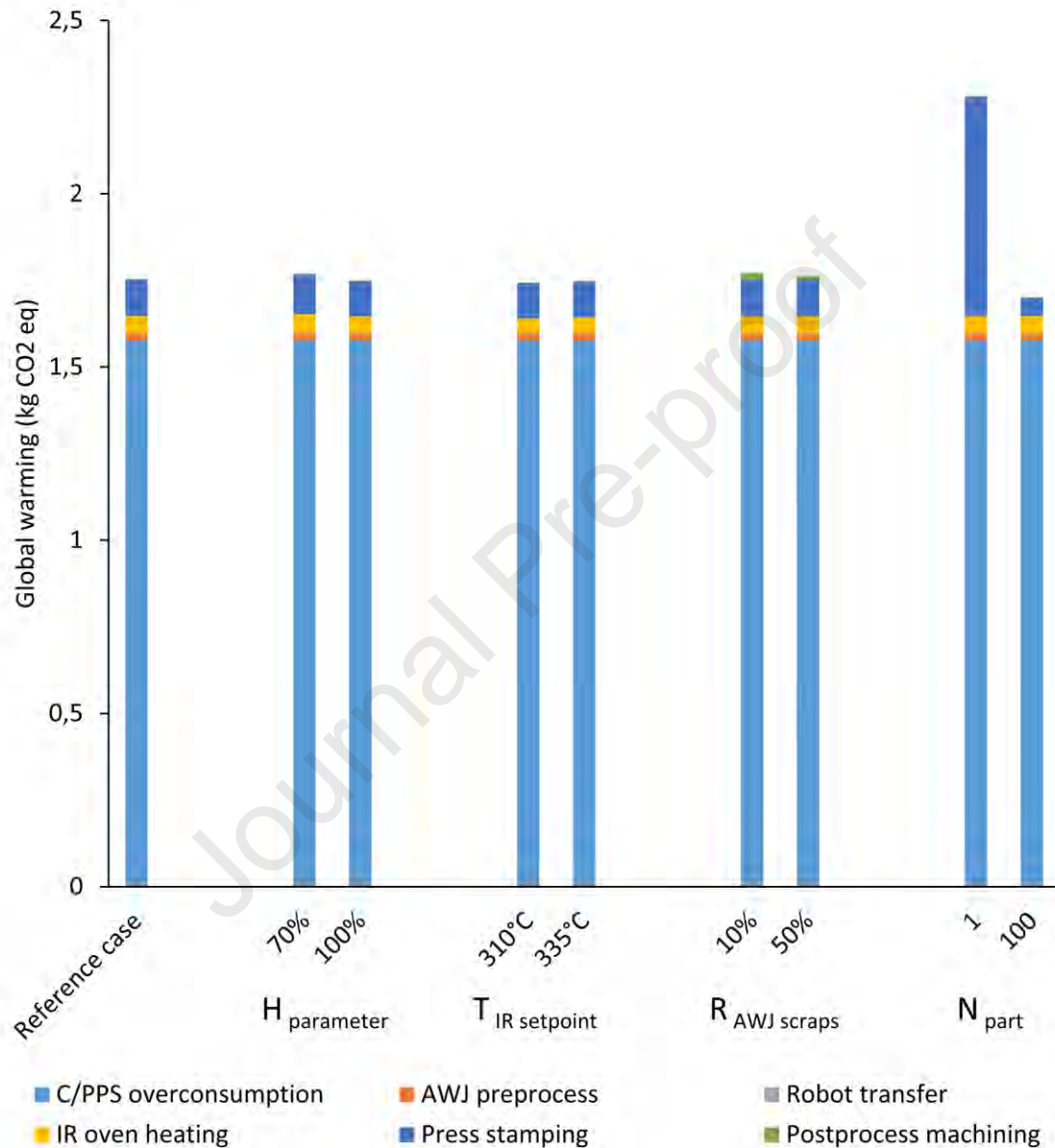


Figure 8: Sensitivity analysis results for the global warming indicator.

6. Discussion

In this paper, we proposed a complete description of the C/PPS thermo-stamping process linked to inventory flow models expressed as functions of the process parameters. We used different strategies to collect the data needed to model the listed inventory flows. On the one hand, some electrical models have been based on experimental measurements at the laboratory scale. It ensures a good correlation between the developed models and the manufacturing process studied in this paper. On the other hand, some models were based on other data sources such as literature,

machine specifications, and the ecoinvent database, which could lead to different levels of accuracy. For example, the global material consumption model was based on the mean of literature data and gave a fast and rough estimate of material consumption. Indeed, it does not consider the process specificity such as the blank holder or the part geometry, which influences material consumption. Models for air emissions have also been proposed in this paper, initially based on experimental measurements that have produced inconclusive results. However, a rough model has been developed using these inconclusive results with the specifications of the measuring machines. This rough model is supposed to overestimate air emissions. Yet, this model is an advance as very few papers gave information about air emissions during the manufacturing process but complementary work still needs to be achieved on this topic.

The proposed models allow for computing inventory data for different parts and process parameters, contrary to the data linked to a fixed case study that can be available in the literature. Thus, we proposed applying the developed inventory flow models to assess the environmental impact of manufacturing a case study part. Results show the cause of the major environmental impact. The over-consumption of materials is the main source of impact and these impacts are driven by the carbon fibre production process. This could be expected as carbon fibre production is known to be an energy intensive process. Then, the impact of the heating and stamping steps is found to be significant. The environmental impact of these steps is mainly due to the electrical energy consumption of the press and oven which is mainly converted into heat to melt the C/PPS in the oven and to control the mould temperature. Furthermore, the case study results show that the gaseous compound contribution and PM emission contribution to the process environmental impact is low, despite the overestimation of this flow. Thus, it could validate our approach to quantify these flows. Finally, the case study results are strengthened by a sensitivity analysis showing that the major cause of impact remains the same independently of process parameters.

7. Conclusion

A lack of environmental data complicates the search for environmental hotspots to set as priorities for improving the environmental impact of processes. In this paper, we proposed an answer to this lack for C/PPS thermo-stamping process. After a complete description of the manufacturing process associated with a balance of the inventory flows, each inventory flow was modelled as a function of the process parameters. The models have been established on data collected from experimental measurements, literature, machine specifications and ecoinvent database. These models enable the computation of inventory data adaptable to different production scenarios and different set of process parameters. However, using different modelling strategies lead to some sources of uncertainty in the inventory flow models. Therefore, a perspective of this work is to improve the reliability of the developed inventory models. Models could be expanded through new experimental measurement campaigns. Numerical methods and simulation tools can also be developed to compute inventory data such as composite material consumption.

To illustrate the use of the proposed models, the environmental impacts of a case study were assessed. This assessment result, associated with a sensitivity analysis, underlined the manufacturing process environmental hotspots, which are C/PPS material overconsumption followed by the energy consumption of the heating and stamping unit processes. These results could be applied to prioritize actions to be taken to reduce the process's environmental impact. Mixed with technical and economic assessments, these results could also be helpful to improve the manufacturing process.

Finally, the models developed in this paper are specific to the C/PPS material and the thermo-stamping process studied and the associated machines. However, a similar methodology can be

applied to other composite manufacturing processes. So then, another perspective of this work is to propose similar environmental assessments for other composite manufacturing processes. Working in this direction could help to decrease the lack of environmental information about the composite manufacturing process.

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C_i : Consumption or emission factor of inventory flow i

D_i : Flow rate of inventory flow i

E_i : Electrical energy consumption of i

$H_{\text{parameter}}$: IR oven heating power parameter

$L_{\text{AWJ cut}}$: AWJ cut length

m_i : mass of flow i

$M_{\text{C/PPS}}$: C/PPS material density

N_{part} : Number of manufactured parts in the press during one production round

P_i : Electrical power consumption of i

R_i : Scraps rate of i

S_{mould} : Mould surface

$T_{0 \text{ part}}$: Initial temperature of the part before IR heating

T_{emission} : Temperature threshold indicating the start of C/PPS air emissions

t_i : Duration of the state i

$T_{\text{IR setpoint}}$: IR heating setpoint temperature

$V_{\text{IR heating}}$: The heating rate at part surface during IR heating

V_i : Volume of flow i

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- Complete and detailed inventory analysis of the C/ PPS thermo-stamping process
- Inventory flow modelling as a function of the process parameters
- Environmental assessment of manufacturing a case study part
- Identification of primary causes of environmental impact

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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