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Abstract

Toe cap for safety shoes is an extremely important protective equipment to prevent injuries caused by falling objects. It can be considered that more than 600 millions toe caps are disposed every year, without the possibility of disassembly them from the shoes. This represents a serious concern and sustainable solutions must be found to decrease the weight on the environment generated by the safety shoe market. In this context, a valid answer can be found in the use of carbon fiber prepreg scraps that can be employed in a circular economy approach, avoiding their disposal in landfill or through incineration, to produce certified and light toe caps. Unfortunately, carbon fiber scraps are associated to high production cost and environmental impacts (mainly due to the high energy requirement for the manufacturing of carbon fiber). Thus, the development of a zero-waste system is mandatory to achieve a conscious use of the resources. In this paper, a reclaim method for prepreg scraps and the relative manufacturing process for toe caps are assessed from the environmental point of view. The impacts are compared with those of a traditional process based on a thermoplastic material (Polycarbonate). Results demonstrate that the reclaim process is extremely sustainable due to the low energy requirements. However, some improvements of the manufacturing process are necessary to make toe caps realized with prepreg scraps more sustainable than the traditional ones.

Keyword: Life Cycle Assessment, Sustainability, Composite material, Reclaim process, Toe cap, Prepreg

1. Introduction

Workplace safety has become a fundamental aspect for the modern industries. In this context, safety footwear are mandatory PPEs (Personal Protective Equipments) in several environments to prevent foot injuries which can be caused by falling objects. To this purpose, they are equipped with toe caps specifically designed to protect the frontal area of the foot. Toe cap must assure high impact and compression resistance but, at the same time, it must be as light as possible to fulfil the ergonomic requirements of the footwear (Chiou et al., 2012). Nowadays, toe caps can be classified in two categories: metallic and non-metallic. The former are typically realized in high carbon steel or aluminum, materials which emphasize the mechanical properties but which present high density; this implies an increase in the total weight of the footwear (Kuklane et al., 1999). Differently, the latter can be realized in reinforced and unreinforced polymers. Carbon, glass and Kevlar fibers are used to reinforce thermoset and thermoplastic matrices specifically formed to produce high resistance and lightweight composite toe caps (Lee et al., 2005). Unreinforced thermoplastic toe caps are usually produced in High Density Poly Ethylene (HDPE), Polyamide (PA) or Poly Carbonate (PC) and by exploiting an injection molding process (Kropidłowska et al., 2021).

Among others, carbon fiber composite toe caps represent the best solution to meet the protective and functional requirements specified in the EU Regulation 2016/425 and in the EN ISO 22568-2:2019 and to minimize the weight of the footwear. However, their manufacturing is a high energy intensive process mainly due to the production of carbon fiber (Duflou et al., 2009). Moreover, carbon fiber composite toe caps, especially as thermoset matrices are used, present serious concerns when they have to be disposed. As reported in the directive 2008/98/EC of the European Parliament (European Parliament, 2008), recycling, along with prevention of waste production and reuse, is a desirable end-of-life option for Carbon Fiber Reinforced Polymers (CFRP) waste; it avoids solutions with higher impacts (i.e. incineration and landfill) and it allows to save virgin materials, leading to significant environmental benefits (Meng et al., 2018). Over the years, several recycling methods for CFRPs based on mechanical, thermal (e.g. pyrolysis and fluidised bed process) and chemical processes have been developed (Asmatulu et al., 2014)(Oliveux et al., 2015). However, there are still some issues with the recycling of thermosets composites. Thermosetting polymers, both in uncured and cured form, are characterised by a cross-linked structure which, differently from thermoplastics polymers, cannot be remelted and easily reshaped and reused (Wang et al., 2018). Depolymerization is not a practical solution for the most commons thermosetting resins, that are typically recovered as filler, fuel or chemical feedstock (Pickering, 2006).

New methods to reduce the environmental impacts of composite materials are continuously under development. One of these is the reclaim process of uncured prepreg scraps. Thanks to an innovative process, the scraps generated during the cutting operations of virgin preimpregnated rolls (off-cuts, trim waste and end-roll waste), which constitute between 20 and 50% wt (in weight) of the virgin prepreg used, can be recovered (Nilakantan et al., 2014). The process is based on the use of specially developed machines able to automatically cut the scraps into small chips and to remove the polyethylene backing paper; in this way, the wastes are prepared for new production processes, preventing them to end up in landfill or incinerator. Moreover, being the scraps uncured, it is possible to reuse both the thermoset matrix and the carbon fibers, reaching a 100% valorisation of the waste. This system has been developed within an European founded project (“CIRCE | Circular Economy Model for Carbon Fibre Prepregs,” n.d.) which has the aim of demonstrating the feasibility of the reclaim process and the sustainable manufacturing of toe caps.

The use of prepreg scraps as a secondary material has already been evaluated in some previous studies in which the authors focus on the feasibility of reusing scraps for the production of composite parts (Nilakantan and Nutt, 2018)(Souza et al., 2017)(Wu et al., 2018). Specifically, it was demonstrated that prepreg scraps can be affordably reused in compression molding processes to realize high quality laminates with very limited environmental impacts (Bianchi et al., 2021).

The reclaim process of prepreg scrap is a new method which must be deeply investigated to understand the potential environmental saving. To this purpose, a case study concerning the manufacturing of composite toe caps exploiting carbon fiber thermosetting prepreg scraps was analysed. The reclaimed material is used for the manufacturing of high quality composite toe caps for work footwear by using a compression molding (CM) process and the environmental impacts, analysed through the life cycle methodology, have been evaluated. Furthermore, they were compared to those of carbon fiber thermoplastic composite toe caps produced by exploiting traditional injection molding (IM) process, the process traditionally performed by a company partner of the CIRCE project. Injection molding is one of the most commonly used technology for plastic parts manufacturing. It is a cost-effective process and it is suitable for high volume production as it is can be fully automated (Wang et al., 2013). It allows to produce complex parts with little or no additional post-production operations and it provides a good surface finish (Guevara-Morales and Figueroa-López, 2014).

In literature, environmental studies concerning the manufacturing of toe caps are not available, even though this protection represents a very impactful part of the shoe. More than 600 millions toe caps are disposed every year, without any possibilities of recycling due to the extremely complicated disassembly procedure. Therefore, the comparison between injection molding and compression molding processes will help to determine whether the recovered prepreg scraps can be employed as an environmental sustainable solution to replace traditional thermoplastic materials, with important consequences for industrial productions.

The Life Cycle Assessment (LCA), conducted in accordance with the ISO standard 14040-14044 (ISO UNIEN, 2010)(ISO UNIEN, 2011), comprises the analyses of raw materials, of the scraps recovery process, of the CM and IM processes and of the End of Life (EoL).

The paper is organised as follows: after the introduction, Section 2 reports the methodologies of the study. The recovery process and the environmental impact analysis are briefly described; the different phases of the LCA that were carried out (Goal and Scope Definition, Life Cycle Inventory and Life Cycle Impact Assessment) are thus detailed. Section 3 presents the results, their discussion and sensitivity analysis. Section 4 summarizes the conclusion of this paper and proposes future research directions.

2. Methodologies

2.1. *Goal and scope definition*

The environmental impacts analysis was performed considering the standard methodology of Life Cycle Assessment (LCA) described by the ISO 14040-14044 normative (ISO UNIEN, 2011)(ISO UNIEN, 2010). The 4 iterative main stages of LCA were followed: Goal and scope definition, Life

Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Results and discussion. The software SimaPro 8.0.5.13 has been used to carry out the analysis.

The functional unit for this life cycle analysis is the manufacturing of a toe cap used in the production of a size 8 (US) work footwear that fulfils the requirements defined by the UNI EN 20345 standard in terms of impact and compression resistance.

More specifically, the toe caps identified in the functional unit must provide a minimum interior height clearance between 18.0 and 20.0 mm when subjected to a standard 200-joule impact test (equivalent to an impact of 20 kg weight as it is dropped from a height of 1 m) and when subjected to a 15 kN compression force.

At present, the toe caps are realized in a thermoplastic polymer-based compound by means of an injection molding process. The main constituent of this part is polycarbonate and it weights 0.077 kg. The manufacturers are evaluating the replacement of the current production system with a compression molding process that uses the recovered thermosetting prepreg scraps as a raw secondary material. The CM process is currently under optimization and the recycled material prototype that was produced weights 0.073 kg.

The goal of this analysis is to quantify and compare the environmental performances of the two processes for the production of one toe cap. Two scenarios were considered in this comparative analysis to represent the traditional injection molding and the innovative compression molding systems.

The Life Cycle Assessment that was carried out can be classified as a “cradle to gate analysis”. It considers all the impacts related to the extraction of raw materials, the materials manufacturing and preparation phases, the materials transport, the production phases and the disposal of the consumables used during the production processes. The use phase the toe caps is not considered within the system boundaries because it would lead to negligible impacts and it would not influence the comparative analysis. The two scenarios are described as follows:

- Scenario 1

Scenario 1 deals with the production of the toe cap through a traditional injection molding process. It uses a granulated compound mainly composed by polycarbonate. Details about the composition of the raw material cannot be reported due to confidentiality reasons. After the production and transport of the thermoplastic compound, it is kept in a dryer for 3-8 hours to remove the moisture from the pellets in order to avoid a reduction in the mechanical properties of the final products (Chhanda et al., 2014). After the drying, the pellets are put in the hooper of an IM machine for the molding phase. A rotating screw moves the plastic toward the mold while, due to the combined effects of the heat friction generated by the screw and heaters positioned outside the barrel, the material melts. Then the screw, acting as a piston, forces the polymer inside the mold. The clamping unit captures the material into the mold and, under controlled conditions of temperature and pressure, forms the plastic components.

The injection cycle lasts only 65 seconds and four parts are produced for each cycle. The moulding protrusions are automatically trimmed and are subsequently reused for the production of new toe caps. It can therefore be considered that no waste material is produced during the injection phase. The molds used in the process are made of steel and are considered to be recycled at the end of their useful life. To facilitate the parts extraction, the mold surfaces are covered with a release agent.

- Scenario 2

Scenario 2 considers the production of the functional unit through a compression molding process using recovered prepreg scraps as a raw material. The recovery process developed within the CIRCE project is based on the use of two specifically designed machines that allow the preparation of the prepreg scraps in order to use them as raw secondary material. The machines are able to reduce the size of the prepreg scraps creating rectangular chips and to remove the polyethylene (PE) backing paper. Once the raw secondary material is prepared, it has to be stored in an industrial refrigerator (at around -18°C) to avoid complete curing of the thermoset matrix (Blass et al., 2017).

After the transportation phase and the refrigerated storage period, the scraps are used in compression molding process. The prepreg chips are manually placed inside the mold cavity and controlled pressure and temperature are applied by means of a press. In this way, the matrix polymerizes and a compact laminate part is produced. The weight of a size 8 composite toe cap produced with reclaimed prepreg scraps and that fulfils the UNI EN 20345 requirements is around 73g.

Currently, a two-cavity aluminium mold is used. The molds are coated with a release agent to facilitate the extraction of the produced part. In both the scenarios, the tooling phase considers the raw materials extraction, the molds machining by means of a CNC machine, the transport and the End-of-Life (by recycling) of the tools. The polyethylene release paper of the scraps is sent to landfill disposal.

Since complete curing of the thermosetting resin must be achieved during the molding phase, scenario 2 is a more time-consuming process with respect to scenario 1. Moreover, being still under development, it is not automated and it strongly relies on manpower.

The manufacturing phases of the machines (e.g. the cutting and peeling machine, the injection molding machine, the press, etc.) as well of the dryer filters are considered out of the system boundaries since, as demonstrated by previous LCA analysis (Germani et al., 2014), their impacts would be negligible due to their long useful life compared to the functional unit production time.

Figure 2 shows all the production phases considered in the two scenarios.

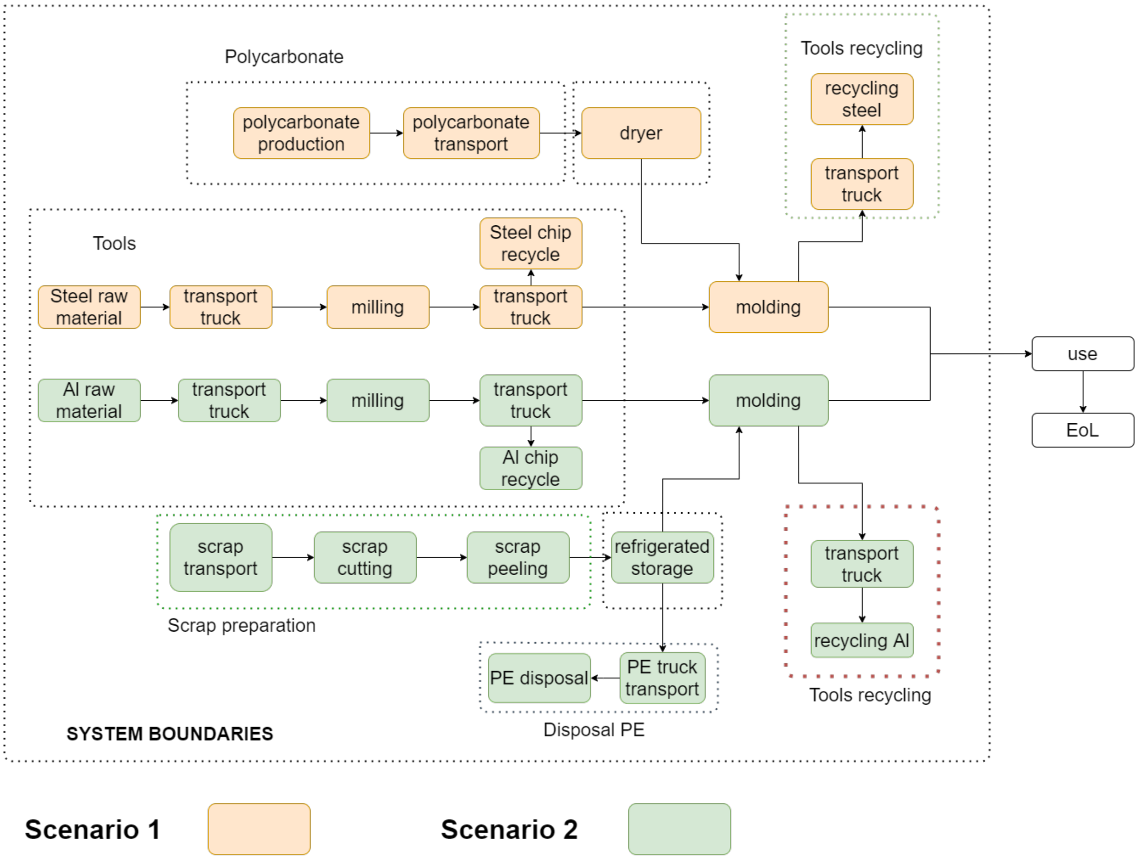

Figure 1 System boundaries of the two scenarios

2.2. Life Cycle Inventory

The inventory data derive from several sources: primary data were collected by the involved companies, whilst secondary data were retrieved from literature research and from the Ecoinvent 3.1 commercial database, integrated by default in SimaPro software (the system model “allocation default” version was used (Wernet et al., 2016)).

The main input material of Scenario 1 is the thermoplastic compound used as feedstock for the injection molding machine. It was considered constituted only by polycarbonate which is the most present element in the blend. Regarding Scenario 2, the waste used as input for the recovery process were considered carrying no burdens from the virgin material production phases; this model was widely used in the scientific literature and it is referred to as “zero-burden approach” (Karuppannan Gopalraj et al., 2021). This choice is suitable for the performed Life Cycle Assessment analysis since the prepreg wastes have no commercial value and they are typically disposed in landfill facilities. The energy consumption of the recovery process machines (cutting and peeling machines) was calculated considering their productivity, their rated power and the weight of one toe cap. The quantity of each material used in the two scenarios was directly measured by the involved companies.

Scenario 1 uses 40CrMnNiMo8-6-1 steel tools (mold and countermold) that, according to the industrial experience of the involved company, have a useful life of 10 years. Their weight data (before and after the machining processes) were calculated considering their 3D models. Scenario 2 uses aluminium tools with an estimated service life of 750 molding cycles(Forcellese et al., 2020); as for the previous scenario, the molds weight before and after machining were obtained considering their 3D models. Inventory data related to the raw materials (aluminium and steel) and the energy consumption of the milling phase of the tools have been derived from the Ecoinvent database. To associate the tooling phase with the functional unit, the environmental impacts of the molds production and disposal were divided, for each scenario, by the maximum number of toe caps that can be produced using a set of tools.

The energy consumptions of the injection molding machine and the dryer were directly measured; considering that for every molding cycle four parts are realised, the electrical energy associated with the production of one toe cap was calculated by dividing by four the energy consumption of one injection cycle. The energy consumption of the drying phase was calculated according to the following equation:

$$D = \frac{w \cdot t \cdot E}{C}$$

with:

- D, the energy consumption of the drying process referred to the functional unit (kWh)
- w, the weight of one toe cap (kg)
- C, the capacity of the dryer (kg)
- t, the drying time (h)
- E, the energy consumption of the dryer per hour (kWh/h)

The energy consumption of the press for the CM process was measured as well and it was associated with the functional considering that 2 parts are produced for every molding cycle.

Table 1 Life Cycle Inventory data

	Item		Quantity	
			Scenario 1	**Scenario 2**
Input materials		Material		
IM raw material	Injection molding compound	Polycarbonate	0.077 kg	-
Prepreg	Prepreg scraps input	Prepreg	-	0.073 kg
	Prepreg scraps PE release	Polyethylene (PE)	-	0.0078 kg
Lay-up	Release agent	Organic solvent	-	0.0075 kg
Equipment		Material		
Mold	Input steel		77.18 kg	-
	Steel mold final weight		62.41 kg	-
	Input aluminium	Raw aluminium	-	31.25 kg
	Aluminium mold final weight	Aluminium	-	25 kg
Countermold	Input steel		27.95 kg	-
	Steel mold final weight		16.38 kg	-
	Input aluminium	Raw aluminium	-	31.25 kg
	Aluminium countermold final weight	Aluminium	-	31.25 kg
Electric energy consumption				
	Dryer	Electric energy	0.013 kWh	-
	Injection molding machine		0.27 kWh	-
	Cutting prepreg scraps		-	0.00038 kWh
	Peeling prepreg scraps		-	0.0064 kWh
	Curing compression molding		-	0.45 kWh
	Refrigerated storage		-	0.066 kWh
Transportation		Transportation typology		
Raw materials	Polycarbonate	Truck 16-32 ton	1000 km	-
	Prepreg scraps		-	344 km
Tools	Raw aluminium and steel		650 km	
	Aluminium and steel molds and countermolds		180 km	
	Steel and aluminium chips		650 km	

Transport data were evaluated considering the geographical location of the involved companies suppliers; inventory data related to the transportation process derive from the Ecoinvent database. The transport of the release agent was not considered as, due to its low weight, it would have led to negligible impacts. Table 1 reports a summary of the inventory data of materials, energy consumption and transport used to assess the environmental impacts of the 2 production processes.

2.3. Life Cycle Impact Assessment

The inventory data can be translated into environmental impacts by means of a large variety of assessment methods (e.g. CML, ILCD) and indicators (e.g. ozone depletion, terrestrial acidification). In order to obtain relevant and complete results, three impact measures were chosen. First, Cumulative Energy Demand (CED, expressed in MJ) quantifies the total energy (direct and indirect) used in all the phases included within the system boundaries. Considering that the composites industry is often energy intensive, CED is an effective indicator of the overall environmental impact of these products and it has been widely used in previous literature studies(Vita et al., 2019). Second, Global Warming Potential (GWP, expressed in kg CO_2 eq) quantifies the greenhouse-gases (GHG) emissions in the atmosphere and their effects on climate change. The methodology described by the Intergovernmental Panel on Climate Change (IPCC) was followed (Khalil, 2017). The third assessment methodology is the ReCiPe Endpoint (H)-Europe H/H single score (expressed in milli-ecopoints, mPt) that consists of aggregate environmental impacts scores at midpoint and endpoint levels (Goedkoop et al., 2009). For the sake of completeness, the results are reported in terms of the ReCiPe midpoint categories too. As for the previous indicators, the ReCiPe methodology has been widely used in previous literature analyses (Forcellese et al., 2020)(Witik et al., 2011)(Duflou et al., 2012).

3. Results and discussion

3.1. LCIA results

The CED and GWP results are shown in Figure 2. The contributions of all the production phases for the total impacts of the two scenarios are shown too. It can be noted that the results have similar trend for the two categories and scenario 1 has always the lowest environmental impacts.

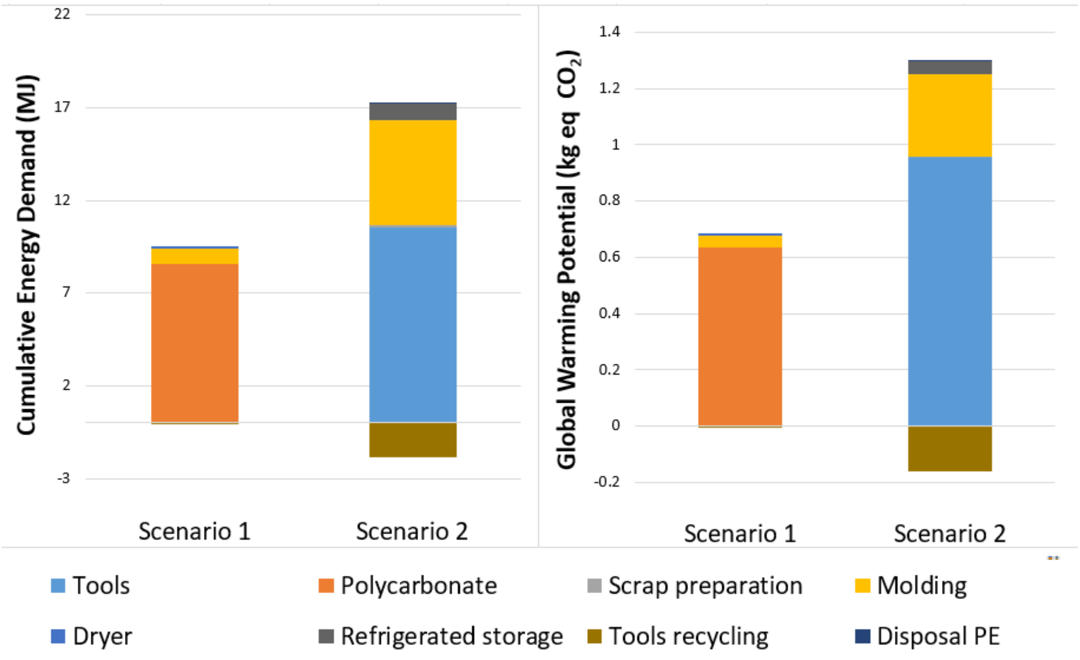

Figure 2 Life cycle impact assessment of the two scenarios in terms of CED and GWP

Specifically, the injection molding process has a Cumulative Energy Demand of 9.5 MJ, which is around 40% lower than that of Scenario 2 (which is 15.2 MJ). The highest contribution for Scenario 1 is associated with the production of the raw materials used. In fact, the polycarbonate input accounts around 90% of the overall impacts (8.6 MJ out of a total of 9.5 MJ). The impact of the steel mold production is negligible due to their long-useful life expectancy. In Scenario 2, the waste recovery process has a negligible impact due to the little electrical energy required (~0.01% of the total impacts). This is a remarkable result considering the high technological value of the recovered scraps; the new process allows to obtain a raw secondary material with mechanical characteristics similar to those of a Sheet Molding Compound (SMC) (Nilakantan and Nutt, 2018) with a practically zero environmental cost. The main contribution related to the recovered prepreg scraps use is determined by the refrigerated storage phase; depending on the considered impact categories, it accounts between 4.1% and 5.5% of the total environmental burden of Scenario 2.

The impacts of the CM process are mainly determined by the aluminium molds production and the molding phases, which have respectively a CED of 10.5 MJ and 5.7 MJ and account together around 95% of the scenario total carbon footprint. Concerning the tools production phase, its impacts are primarily derived from the raw material extraction while the machining and transport phases have little influence on the total footprint. On the other hand, the molding phase of Scenario 1 has very low impacts (0.79 MJ). This behaviour can be attributed to the different chemical composition of the materials used: the thermosetting matrix of the recovered prepreg scraps requires a time consuming (and high energy consuming) curing process to be hardened whilst the thermoplastic compound gains rigidity just by rapidly cooling down. About the tooling phase, the strong environmental impacts of Scenario 2 are determined by two factors: 1) the short useful life of the aluminium molds (of only 750 molding cycle); 2) the high energy consumption required for the production of raw aluminium (Peng et al., 2019). The negative contribution of the total environmental impacts of the two scenarios are determined by the recycling process of the molds; as for the tools production, in Scenario 2 the aluminium recycling has a great relevance as the impacts of the process are distributed on a small number of produced parts. Other production phases such as transport, polycarbonate drying and PE film disposal have little influence on the overall impacts.

Considering the Global Warming Potential results, Scenario 1 has equivalent CO_2 emissions of 0.63 kg whilst an impact value of 1.14 kg eq CO2 is reached by Scenario 2. The trend is very similar to that observed for CED; the impacts of Scenario 1 are mainly determined by the polycarbonate (which causes a value of 0.63 kg eq CO_2) whilst those of Scenario 2 primarily depend on the tooling and curing phase, which accounts respectively 0.96 and 0.29 kg eq CO_2.

The values obtained for the 18 ReCiPe midpoint categories are reported in Table 2. The compression molding process has the highest environmental load for the majority of the midpoint categories. Two exceptions are the “ozone depletion” and the “terrestrial ecotoxicity” for which the injection molding process has the highest environmental impact. This is mainly caused by the high influence of the polycarbonate production (i.e. more than 95% of the value of the ozone depletion impact indicator). Moreover, for these two environmental impact categories, the aluminium extraction in Scenario 2 has a lower contribution with respect to most of the other impact categories.

Table 2 ReCiPe midpoint results

Impact category	**Unit of measure**	**Scenario 1**	**Scenario 2**
Climate change	kg CO2 eq	6.70E-01	1.13E+00
Ozone depletion	kg CFC-11 eq	2.10E-07	4.60E-08
Terrestrial acidification	kg SO2 eq	2.02E-03	7.72E-03
Freshwater eutrophication	kg P eq	2.75E-05	2.91E-04
Marine eutrophication	kg N eq	3.82E-04	9.49E-04
Human toxicity	kg 1,4-DB eq	6.35E-02	3.04E-01
Photochemical oxidant formation	kg NMVOC	1.67E-03	3.90E-03
Particulate matter formation	kg PM10 eq	9.84E-04	2.69E-03
Terrestrial ecotoxicity	kg 1,4-DB eq	2.58E-05	2.24E-05
Freshwater ecotoxicity	kg 1,4-DB eq	2.27E-03	1.46E-02
Marine ecotoxicity	kg 1,4-DB eq	2.07E-03	1.37E-02
Ionising radiation	kBq U235 eq	1.07E-02	6.55E-02
Agricultural land occupation	m2a	2.47E-03	3.05E-03
Urban land occupation	m2a	1.31E-03	8.54E-03
Natural land transformation	m2	1.52E-05	1.49E-04

Water depletion	m3	4.47E-03	6.83E-03
Metal depletion	kg Fe eq	3.38E-03	3.63E-03
Fossil depletion	kg oil eq	1.91E-01	2.75E-01

As shown in Figure 3, the midpoint categories were aggregated into the three endpoint damage categories of the ReCiPe methodology. For both the production processes, the most critical damage categories is “Human health”, which determines 43% and 49% of the single score values for Scenario 1 and Scenario 2 respectively. The second most relevant contribution to the single score value is given by the “Resources” damage category; it accounts 36% of the impacts for Scenario 1 mainly due to the polycarbonate production. For Scenario 2, it determines 29% of the value of the ReCiPe single score and it is primarily caused by the aluminium employed in the tooling phase.

Scenario 1 obtained a value of 57.16 mPt for the ReCiPe single score impact indicator whilst Scenario 2 reached a value of 100.01 mPt. Once again, the environmental behaviour of the different production phases echoes that observed for the previous impact indicators.

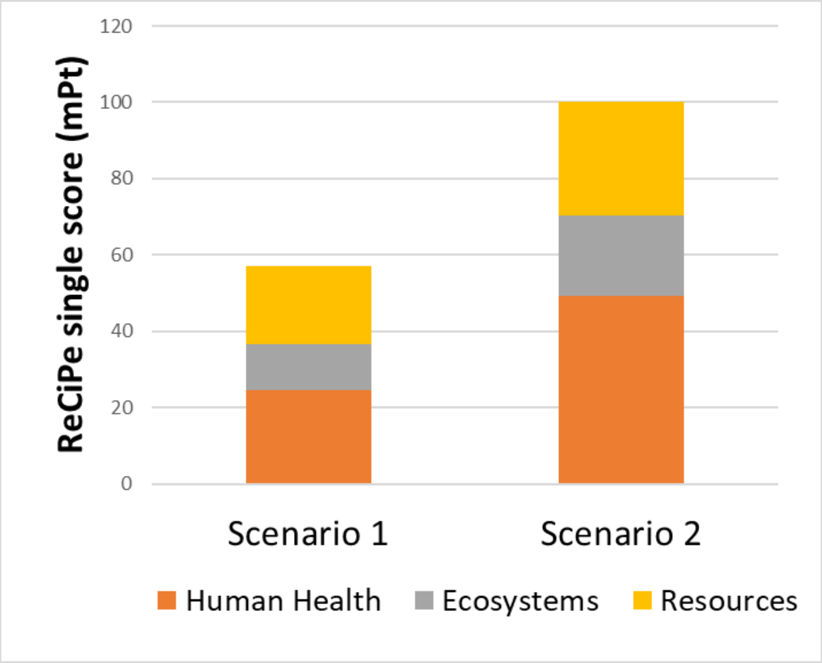

Figure 3 ReCiPe endpoint results for the two scenarios

As reported above, the reclaim process for prepreg scraps is extremely sustainable as the energy consumption of the machines used to transform the scraps is about 0.09 KWh/kg (0.3 MJ/kg). It is worth to notice that the proposed reclaim process allows to recover both matrix and fibers without compromising fibers integrity. Differently, the common recycling processes for composite materials (pyrolysis, fluidised bed, mechanical recycling, etc.) do not allow to recover the matrix and, typically, the recycled carbon fibers present lower mechanical properties with respect to the virgin ones. Moreover, as the energy consumption of the EoL alternatives for composites are compared, it is evident that the proposed reclaim method is at least 7 times more sustainable. In Table 3, a comparison between the energy consumption of the proposed method and pyrolysis, fluidised bed and mechanical recycling processes is reported.

Table 3: Comparison between alternative recycling methods for CFRP

Process	**Energy consumption (MJ/kg)**	**Outputs**	**Source**
Pyrolysis	30	Short low-quality fibers. No matrix.	(Witik et al., 2013)
Fluidised bed	6	Short low-quality fibers. No matrix.	(Meng et al., 2017)
Mechanical recycling	2.03	Dust, filler. Extreme low quality.	(Howarth et al., 2014)
Proposed system	0.3	Uncured high-quality composite.	

The proposed reclaim system for composite prepreg scraps can be also used in other circular applications. As an example, if the scraps are obtained from unidirectional materials or are appropriately oriented in one direction, they can be used for semi structural components such as reinforcing ribs for the automotive or aerospace sectors. Moreover, randomly oriented woven fabric scraps can be also employed in aesthetic components due to their inhomogeneity, emulating the effect of the so-called Forged Composites® developed by Lamborghini.

3.2. Sensitivity analysis

Further analyses were conducted to identify the critical variables of the production processes that are those whose variations most influence the results. A sensitivity analysis was carried out by ranging one production phase impacts at the time, keeping unchanged the other values, and calculating the difference between the environmental impacts of the two scenarios. The impacts of the most relevant phases of the production systems were assessed and ranged between -100% and +100% of their initial values. In this way, it was possible to simultaneously consider all the variables of the relevant production phases. This has also allowed to calculate the switching values, i.e. the values that the different variables must attain to make the difference between the two scenarios impacts equal to zero.

Figure 4 shows the results of the sensitivity analysis for the Cumulative Energy Demand; similar results were obtained considering the other two impact categories. The values on the x-axis indicate the percentage variations of the impacts of the considered phases while the vertical axis represent the difference in impacts between scenario 1 and scenario 2. All curves intersect in the point that corresponds to a null variation of the analysed production phases. The variables whose have the largest impact on the environmental analysis are those related to the aluminium molds production (which is always the steepest curve), and polycarbonate. These are the only variables for which a switching point is reached; in the other cases, the impacts difference would not become 0 even if the variable were 0.

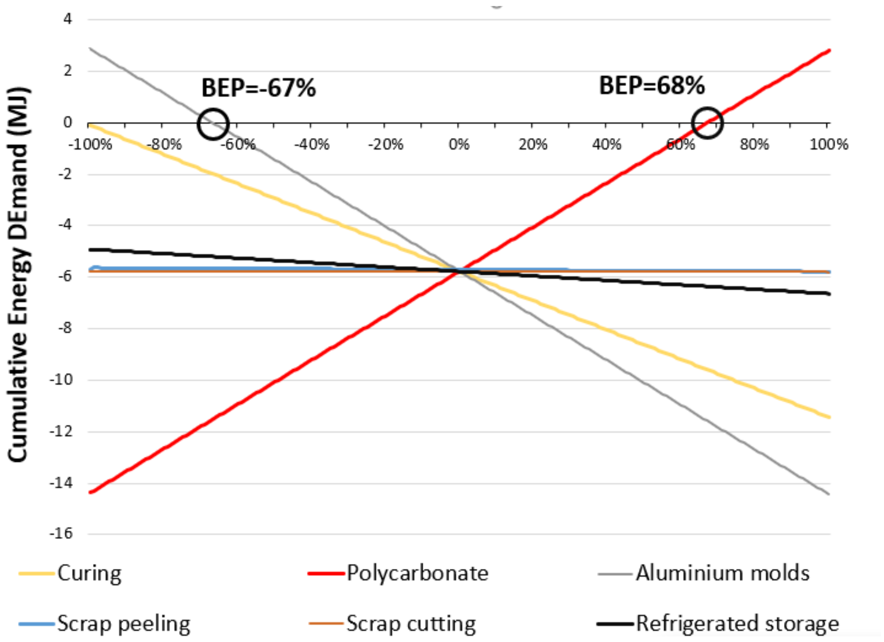

Figure 4 Break Even Points of the two investigated scenarios

Given the considerable relevance of the tooling phase for Scenario 2, this phase has been examined in greater detail. Excluding the impacts related to the molds productions and considering all the other processes, Scenario 2 would have a better environmental performance in terms of all the considered environmental indicators. Figure 5 reports the total Cumulative Energy Demand as a function of the total parts produced each year; if the compression molding molds service life could be extended by at least three times the present useful life, for example by using a wear-resistant material, a break-even point would be reached for a production volume of about 4500 parts per year.

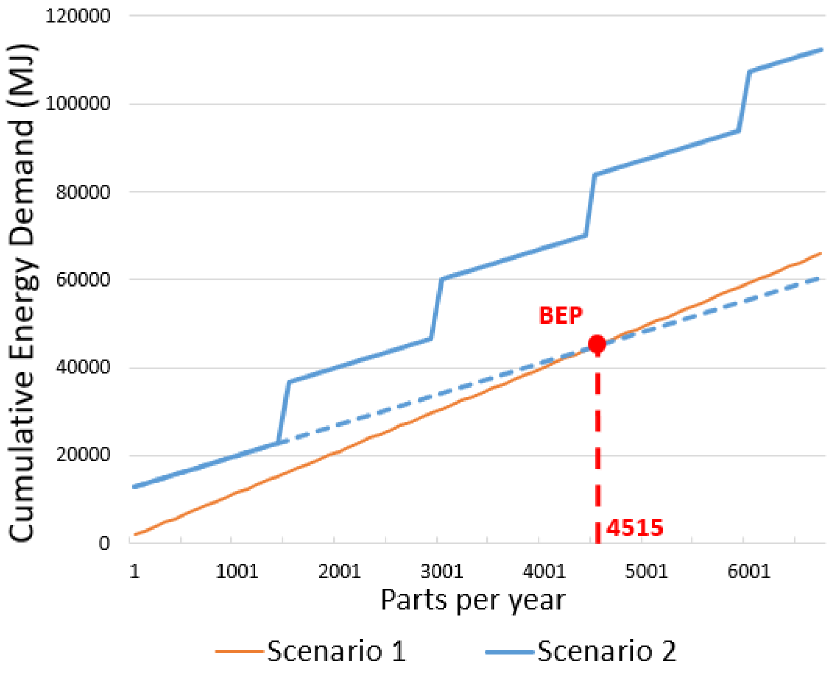

Figure 5 Break Even Point related to toe caps production per year

4. Conclusions and further development

In this paper, the analysis of the environmental impacts through the life cycle of composite toe caps realized with reclaimed carbon fiber reinforced polymer has been conducted.

A Life Cycle Assessment analysis was performed to evaluate the environmental impacts of the recovery process for prepreg scraps and of the manufacturing of the composite toe caps through a compression molding process. The results were compared to a traditional injection molding process used to realized polycarbonate toe caps. The functional unit that was chosen is the production of a toe cap used in work footwear and impacts from the extraction of raw material to the factory gate (cradle to gate analysis) were considered. The impacts were evaluated using different indicators (CED, GWP and ReCiPe at both the midpoint and endpoint) in order to have a complete vision of the environmental effects of the two scenarios. In addition, a sensitivity analysis was carried out to improve results reliability and investigate improvement possibilities.

The main results are listed below:

- For the most part of the considered impact categories, the traditional injection molding process has proved to be the best environmental alternative (with impacts about 40% lower than the innovative alternative). This may be justified considering that the IM process uses a thermoplastic raw material, which requires little time and low energy consumptions to be moulded. In addition, the recovery process is still under development and further improvements are needed.
- The machines used for the recycling process have low energy consumptions and, subsequently, negligible environmental impacts. This makes the new process of great industrial interest considering the high mechanical properties of the secondary material.
- The polycarbonate constitutes the highest contribution to the impacts of the injection molding scenario (e.g. 8.5 MJ out of the total 9.5 MJ for the CED indicator).
- The impacts of the compression molding process are mainly determined by the curing phase and the molds production. A reduction in impacts of the latter could make the recovery process the best environmental alternatives (switching points are reached for a variation of -67% and 68% of the molding phase for the CED, GWP, and ReCiPe single score respectively).
- Extending the service life of the compression molding aluminium tools up to 4500 cycles would make the recovery process the lowest impact scenario.

Considering what emerged from this analysis, further development will be focused on the optimization of the recovery scenario. As an example, the use of steel molds, which present a longer service life, will allow to reduce the environmental impacts of the tools manufacturing. In this way, the recovered material scenario could become the best environmental solution. In addition, by exploiting the good mechanical properties of the recovered material, lighter parts could be produced, further reducing the environmental impacts of the toe cap production. New environmental analyses will be performed as process upgrades will be made. Moreover, other applications of the recovered material, such as the production of automotive components, may be considered for future works.

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