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Environmental impact analysis of the injection molding process: analysis of the processing of high-density polyethylene parts

Ana Elduque[a,1], Daniel Elduque, Carlos Javierre[a], Ángel Fernández [a],Jorge Santolaria [b]

[a] *i+- aiTIIP, Department of Mechanical Engineering, EINA, University of Zaragoza, C/María de Luna, 3, 50018 Zaragoza, Spain*

[b] *Department of Design and Manufacturing Engineering, EINA, University Of Zaragoza, C/Maria de Luna 3, 50018 Zaragoza, Spain*

Abstract

This paper studies the environmental impact of the injection molding process by carrying out a life cycle assessment. A review of how EcoInvent's Life Cycle Inventory database characterizes this process has been conducted, and a new methodology based on that analysis has been carried out. Aspects such as the infrastructure of the factory or waste treatment are part of the environmental impact of the injection molding process, but the most significant factor is electricity consumption; therefore, electricity consumption measurements of the process have been performed. This environmental analysis has been applied to the processing of several parts made of high-density polyethylene, which have been characterized by measuring the electricity consumption. As a consequence of this work, it has been proven that electricity consumption can be used as an injection molding machine selection criteria, from an environmental standpoint, as it produces the highest environmental burden of the process.

Keywords: Injection Molding; Environmental Impact; HDPE; Electricity Consumption; LCA

1. Introduction.

Today, plastics are one of the most used polyvalent materials and are an important part of the economy. They provide multiple applications in a wide range of sectors, from the packaging market, which represents 39,4% of the demand for plastics, to the building and construction sector, the automotive industry and other examples, such as home appliances or medical products (PlasticsEurope, 2013).

Among the different types of plastics, the three most demanded are the thermoplastic variations, polypropylene (PP), low-density polyethylene (LDPE) and high-density

[1] * Corresponding author. Tel.: +34 876555211; fax: +34 976761861

E-mail address: anaelduque@gmail.com

polyethylene (HDPE), according to (PlasticsEurope, 2013). The last one represents 12% of the total European plastic demand (PlasticsEurope, 2013). Injection molding is one of the most used plastic part manufacturing processes due to its precision and cost-effectiveness for large volume productions (Wang, et al., 2013), (Guevara-Morales & Figueroa-López, 2014). This process is divided into five phases: mold filling, packing, the simultaneously occurring cooling phase and plasticizing phase, and finally the ejection of the injected part. All of these phases make this process quite intensive, energetically speaking. Thus, that high electricity consumption also implies that the injection molding process is also relevant in terms of environmental impact, even more so bearing in mind the large scale of plastic parts manufacturing.

There are different types of injection molding machines depending on how the drives are powered: hydraulic, hybrid and all-electric. In the hydraulic type, the injection molding machine's motions are powered by hydraulic pumps. Today, almost no machinery is purely hydraulic as they typically use hybrid mechanisms, such as the toggle clamping mechanism that helps the hydraulic system and also provides electrical energy savings (Huang, et al., 2011), (Hsu, et al., 2013). All-electric injection molding machines replace the hydraulic circuit with servomotors. One of the main specifications that characterize an injection molding machine is its clamping force, and this is related to the size of the parts that can be injected in it. There is a wide range of clamping forces, from micro-injection molding machines of approximately 50 kN of clamping force up to nearly 100000 kN of clamping force (Muccio, 1994). In this paper, injection molding machines from 833 to 78400 kN have been analyzed while manufacturing HDPE parts. This last injection molding machine is one of the largest operating in Spain.

The plastics industry in Europe started to assess the environmental impact of plastics more than 20 years ago (Boustead, 1992). The societal concern regarding this subject is increasing around the world (Givens & Jorgenson, 2013), with the global warming threat as one of the primary reasons (Czap & Czap, 2010). This environmental concern has promoted the use and development of different methodologies that strive for sustainable development. The life cycle assessment (LCA) is a methodology used to calculate the environmental impact of products, processes or services. The results obtained by an LCA are analyzed so that priority areas in which actions should be applied can be identified (Guinée, 2002). Working in those areas allows researchers and designers to improve the environmental performance and, as a consequence, make products and processes more ecofriendly.

In the specific field of injection molding, Thiriez and Gutowski provide a review of the entire process, including the thermoplastic production, the compounding of the additives and the injection molding process (Thiriez & Gutowski, 2006). In that paper, the authors highlight the importance of the choice of the type of the injection molding machine as that could entail a high impact in the specific electricity consumption of the injection molding machine, therefore also influencing, as will be discussed in this paper, the environmental impact of the process. In the thesis of Almeida, a life cycle engineering task was performed, following a cradle-to-grave approach in order to determine the environmental performance of the injection molding of biodegradable plastics (Almeida, 2011). In the article written by Weissman et al., a methodology to estimate the electricity consumption of the injection of a molded part is explained, with the aim of providing an electricity consumption model to help designers make more environmentally conscious decisions (Weissman, et al., 2010).

When performing an LCA of a product, the materials and manufacturing processes have to be identified. Among these processes, the injection molding process is usually included. Databases, such as EcoInvent, have defined the injection molding process based on measurements of several facilities at a European level (Hischier, 2007). In another report (TNO for Plastics Europe, 2010), PP and HDPE along with polyvinyl chloride (PVC), which are among the most demanded plastics, are used as a reference to characterize the environmental impact of the injection molding process.

These values could be used to incorporate them into the calculation of the environmental impact of that product as a first approach. However, if the level of detail required is higher or the injected parts are an important component of the study, this approach is not precise enough. As Gutowski et al. note in their research, the manufacturing process's electrical energy requirements are not independent of the characteristics of the manufactured parts, as the LCA databases traditionally assume (Gutowski & Thiriez, 2006).

The main aim of this essay is to analyze the different factors in the environmental impact of the injection molding process. From this analysis, a methodology is developed to calculate the environmental impact of a specific injection molding process, and it has been applied to several parts that use the same raw material (HDPE). The units of the obtained results will be per injected kilogram.

2. Materials and Methods

In the following section, a review and analysis of the state of the art is going to be presented, as well as the equipment that has been used during this research, such as the raw material, molds and injection molding machines analyzed and the required measurement equipment.

2.1 State of the art review and analysis

Various authors have investigated the electrical energy requirements of plastics manufacturing processes. Muller et al. analyzed the injection molding by using dual electrical energy signatures to determine value- and non-value-adding elements to improve the process's efficiency by studying the influence of the process time and power levels on the injection molding machine (Müller, et al., 2014).

Madan et al. also studied this process by considering its electricity consumption as an indicator of sustainability. They suggest that the LCAs performed today give much more importance to the material than to the manufacturing factors, and they propose a guideline to estimate the electricity consumption of UMPs (unit manufacturing processes), based on the analysis of the stages of the injection molding process, with the goal of benchmarking, evaluation and improvement (Madan, et al., 2014).

Lucchetta and Bariani also conducted research based on this idea, suggesting that most LCE (Life Cycle Engineering) tasks, where the environmental and economic impact of the product are assessed simultaneously, are focused on minimizing the use of materials and increasing the recycled materials but do not take into account the cost and environmental impact of the manufacture of the design alternatives. They also remark on the importance that the injection molding industry has, in terms of environmental impact, due to its large scale (Lucchetta & Bariani, 2010). Yak and Mak studied the gas-assisted injection molding process. This process allows for the reduction of the use of petrochemical polymers and, at the same time, achieves electrical energy savings of 20% thanks to the reduction of processing parameters, such as the injection pressure and the clamping force of the injection molding machine (Yam & Mak, 2014).

The electrical energy demand has also been studied in other plastics manufacturing processes, such as polymer extrusion. For instance, Abeykoon et al. studied the electrical energy demand with different process conditions in order to optimize the process's efficiency (Abeykoon, et al., 2014). Alternately, Deng et al. presented a real-time electricity consumption monitoring method and used it to study the effect of process settings on melt quality and electrical energy efficiency, which are highly related with the electricity consumption (Deng, et al., 2014). Moreover, results in other papers showed that the specific electrical energy demand was reduced as the throughput was increased (Abeykoon, et al., 2014). These experimental studies help to select operational conditions and equipment to optimize the process.

In this research, in order to analyze the environmental impact of the injection molding process, we have studied the injection molding dataset of EcoInvent v3.01 as a starting point (named in this paper as EcoI). To create the dataset for the generic injection molding process, EcoInvent calculates the arithmetic mean of data gathered from three average injection molding processes, PVC, PP and PET (Hischier, 2007), and correlates the inventory data to its own datasets. There are notable differences between input data of the different plastics.

To manufacture one kilogram of injected plastic parts, this inventory includes water used during this process, lubricating oil, and different types of additives, such as chemicals, solvents, pigments or fillers. It also considers packaging materials: pallets, polypropylene, LDPE and cardboard. The electricity, natural gas and other fuels are classified as energy inputs. The generated waste is separated into waste to landfill, hazardous waste and plastic waste from which energy is recovered by incineration. Given that our raw material is going to be high-density polyethylene, we can use the report from which this database has been constructed (Hischier, 2007) and particularize it in order to obtain a more precise approach. Additionally, as the aim of this paper is to determine the environmental impact of the injection molding process for HDPE parts, the first step that has been carried out is to remove those values that do not directly belong to the injection molding process itself (Figure 1), even though they may be necessary to deliver the final product. Therefore, packaging materials and the natural gas or other fuels used to heat the conversion plant are also not going to be considered, as those inputs are highly dependent on the part, factory, etc.

The second step performed in this study is to replace the remaining values with those of the polypropylene report, as this plastic is more similar to the HDPE from the three thermoplastics that EcoInvent uses to characterize its average injection molding process. This way, the dataset could be used to analyze most standard thermoplastics except for the PVC, which needs special treatment due to its chemical composition, as it has to be combined with several additives before processing (Pita, et al., 2001). As we can see in the original data (Hischier, 2007), the PVC injection molding process has specific inputs, such as solvents or stabilizers, that are not used in conventional plastics and therefore are going to be omitted to analyze a standard thermoplastic, such as HDPE. Therefore, these elements would only be considered when PVC processing is the analyzed process.

Finally, EcoInvent's estimation of infrastructure of the plant and machinery is not modified. The following table (Table 1) shows the EcoInvent datasets that have been used in our particularized case for a standard thermoplastic, which is named in the text as CEcoIPP. The steps carried out to obtain this dataset are shown in Figure 1.

As will be shown in the results section, the electricity consumption is the most influential element on the environmental impact, so the electricity consumption of our particular processes are going to be measured to obtain a more precise result.

The final dataset that will be used for the environmental impact of the HDPE parts is that achieved by the steps shown in Figure 2. Figure 3 shows, in a very schematic manner, the elements considered by EcoInvent and those left outside the system boundaries in our study. Emissions are considered as within the system boundaries, using the same methodology as EcoInvent. However, for the particularized case of CEcoIPP, their value is zero because there is no reported data for PP processing in the study (Hischier, 2007).

2.2 Required equipment

The required equipment consists of several injection molding machines (Table 2), HDPE as raw material, bascules to measure the weight of the part that is being injected during the experiment, a timer for measuring the cycle time, and a portable three-phase power analyzer, which measures the power that it is being used during the injection molding process by the injection molding machine and the auxiliary equipment.

The software used to perform LCA calculations is SimaPro 8.0.3.14 (Goedkoop, et al., 2013), developed by Pré Consultants. The EcoInvent v3.01 database (Weidema, et al., 2013) has been used as the main data source for the inventory.

2.2.1 Raw Material

In all of the injection molding processes that have been measured, RIGIDEX 5740 UA HDPE has been used as the raw material.

Some of the properties of this raw material are:

- Density: 0,957 g/cm^3
- Melt Flow Index: 4 g/10 min
- Vicat softening: 125 ºC
- Tensile yield strength: 27 MPa
- Flexural modulus: 1250 MPa

2.2.2 Molds and Injection molding machines

Figure 4 shows all of the HDPE parts for which processes have been measured.

Parts #1 and #2 are the bodies of two waste containers of different capacities, 2400 and 1000 liters, respectively. Part #3 is a lid used for waste containers. Parts #4, #5 and #6 are both different-sized openings through which waste is inserted into the containers. Parts #7 and #8 are smaller parts from other containers. #7 is a shaft that connects to and allows the rotation of a lid on the body container, and part #8 is a plug whose task is to cover some of the container's elements.

All of these parts have been injected in several injection molding machines, which are classified in Table 2, based on their clamping force. All of them are hybrids, except for the 833 kN one, which is an all-electric injection molding machine. Some images of the measured injection molding machines are shown in Figures 5, 6 and 7.

2.2.3 Measurement equipment

This equipment (Figure 8) is formed by a Circutor C-80 power analyzer that records the measurements and other accessories, which include several clamps that measure the current, voltage cables with crocodile clamps that are connected to the electric panel to measure voltage, and, finally, rubber gloves to ensure safety when connecting the devices to the grid.

For this study, three different current clamps have been used, and each one of them is adequate for an interval of electric current. In Figure 8, the power analyzer connected to the electrical panel is shown. In this manner, the C-80 power analyzer registers the average power consumed by the injection molding machine and all auxiliary equipment. The accuracy for the power rating of the instrument is 1%, which is precise enough for these measurements; differences between measurements are much larger than the accuracy of the instrument, so the conclusions drawn from them will not be affected by the precision of the instrument.

2.3 Measurement procedure

Before a measurement begins, the maximum instantaneous current measured by the power analyzer must be checked in order to decide the most suitable current clamp. It is advised by the analyzer's manufacturer to measure in the highest part of the scale for better accuracy. Additionally, it is important that the production is stable during the test so that measurements will not take place during start-up periods. If production stops during the test, the measurement is discarded. The duration of the test with this sampling period is at least three hours. This provides enough data to check and ensure that the production is stable.

To calculate the kWh/kg of the injection molding process, the plastic weight processed per cycle, the cycle time and the measured power of the equipment are obtained. To determine if the measurement value is representative, it is recommended to use a spreadsheet to analyze the gathered data to ensure that the electricity consumption value is stable.

3. Life Cycle Inventory, LCI

According to the methodology explained before, the inventory of our injected molding process will be the dataset collected in Table 1, but the electricity is replaced by the kWh/kg value obtained by our process measurement. EcoInvent's European electrical mix is used.

3.1. Life Cycle Impact Assessment, LCIA

To assess the environmental impact, there are two possible ways of calculating the results: midpoint and endpoint. To avoid the subjectivity of the endpoint approach, methodologies such as CML Leiden, which uses a midpoint approach, can be used (Guinée, 2002). The CML Leiden method is recognized as one of the most widely used in LCA studies (Wäger, et al., 2011) (Monteiro & Freire, 2012).

For these reasons, the results are calculated with the CML Leiden methodology, which computes the environmental impact in all categories of CML: abiotic depletion, abiotic depletion (fossil fuels), global warming (GWP 100), ozone layer depletion (ODP),

human toxicity, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, acidification and eutrophication.
A detailed explanation of these categories can be referred to in guides such as (Guinée, et al., 2002).

3.2. Measured electricity consumptions

In Table 3, the injected weight per cycle is collected, along with its cycle time and the electricity consumption.

There are significant differences between the measured parts. Part #1 consumes less electricity per kilogram with 0,431 kWh/kg, and part #5 has the highest electricity consumption at 2,31 kWh/kg. These results show that the electricity consumptions fluctuate significantly for different parts and injection molding machines. Many of the measurement values are lower than EcoI's average value of 1,47 kWh/kg or the 2,096 kWh/kg reported by (Hischier, 2007) for PP processing (CEcoIPP).

Although there are differences, such as the type of injection molding machine or the geometry, that also have an influence, a clear tendency is observed: parts with high throughput (Kg/h) usually have less electricity consumption per injected kilogram, a tendency that has also been observed by other authors, such as Thiriez and Gutowski for the injection molding process (Thiriez & Gutowski, 2006) and Abeykoon et al. in the extrusion of polymers (Abeykoon, et al., 2014).

For example, it is interesting to analyze the differences between the electricity consumption per kilogram of part #5 and part #6. These parts were both injected in the same injection molding machine (Injection Molding Machine E, Clamping force: 7350 kN) and have similar cycle times. However, the weight of part #6 is more than three times larger than that part #5, and, conversely, its electricity consumption per kilogram is more than three times lower than that of part #5.

4. Results and Discussions

Results for the EcoInvent Dataset, the customized dataset CEcoIPP, and the HDPE injected parts are going to be shown and discussed in this section. Several tables collect the environmental impact results in CML units. Graphics will represent the percentage of the elements of the inventory for each impact category, and a final figure will compare all of the different results.

4.1 EcoInvent Dataset Results (EcoI)

Table 4 shows the total results for the Injection moulding (RER) process of the EcoInvent v3.01 database.

Figure 9 summarizes the contribution of the different elements associated with the injection molding process for each impact category.

In these generic results obtained with the LCI values of the EcoInvent database, the electricity is the most important factor in all of the impact categories, except for the abiotic depletion where the infrastructure has more importance (43,6%) due to the kilograms of steel that is considered for the factory's machinery.

Additives, including solvents and stabilizers, specific to PVC processing are also a significant part of the environmental burden, especially in the photochemical oxidation (33%) and ozone layer depletion (18%) impact categories. Other energy inputs, such as natural gas and other fuels, also contribute notably to the depletion of fossil fuels, the ozone layer depletion and the global warming potential (approximately 15%).

4.2 Customized Dataset result (CEcoIPP)

The results of our modified EcoInvent dataset for analyzing the injection molding process of a conventional thermoplastic are shown in Table 5.

In our customized process (CEcoIPP, Table 1), where specific PVC additives have been removed, along with packaging materials and fuels, the electricity consumed by the injection molding process accounts for more than 94% of the environmental impact in almost every impact category, except for the first one (Table 5), similarly to the EcoI results.

This fact justifies the required equipment and the measurement procedure shown in subsection 2.3. By measuring the electrical consumption of our process, its environmental impact can be calculated in a very accurate way.

Table 6 shows a comparison between the EcoI and the CEcoIPP results. These values can be better understood by taking into account the higher value of electricity consumption for the CEcoIPP (+42,6% over the average electricity consumption of the EcoI dataset) and also the exclusion of inventory data as explained in section 2.1. Some categories, such as both abiotic depletion categories, ODP and photochemical oxidation, show a lower impact on the ecological environment due to the removals explained in section 2.1 (solvents, stabilizers, natural gas, etc.). Alternately, for those categories in which the contribution of the electricity consumption is high (Figure 9), such as human toxicity, all of the ecotoxicity categories, and eutrophication, there is a relevant impact increase.

4.3 HDPE parts results and comparison

In Table 7, the environmental impact of the customized process with the polypropylene values (CEcoIPP) is compared with the results for each measured part.

In Figure 10, it can be seen how the differences between parts in each impact category follow the same proportion the electricity consumption does. Only in the abiotic depletion category are the differences smaller. As has been seen in a previous subsection (4.2 Customized Dataset result (CEcoIPP)), the infrastructure is the most influential element in the abiotic depletion category, and this element was kept constant in the LCI in all cases. Despite this, the electricity also has an influence in this impact category, as is indicated in Table 5 (43% in CEcoIPP results, compared to infrastructure with 56,87%).

Thus, the final results show that there is a great variation due to the electricity contribution. Part #1 involves the lowest environmental impact per kilogram because its electricity consumption is the lowest of the measured parts. Alternately, the processing of one kilogram of part #5 creates an even higher impact than the calculated CEcoIPP due to its electricity consumption of 2,31 kWh/kg.

In view of the results shown in this paper, the results and conclusions of LCA studies that use EcoInvent data for the injection molding process may slightly differ, especially if this process is important for the studied product. For example, consider the study carried out by Rives et al, where a comparison between different systems for municipal solid waste management was made. In that research, the environmental impact of several HDPE containers with different capacities was assessed using the injection molding data of EcoInvent and compared with other steel alternatives. Based on our data, the environmental impact of the injection molding process of these containers, some of them similar to parts #1 and #2, may be lower, but, in this case, it would not affect the overall conclusions as the studied steel containers produce significantly lower environmental impact than the HDPE ones (Rives, et al., 2010).
Pina et al. presented the LCA of several induction hobs (Pina, et al., 2015). The inventories showed several injection molded parts (of PA66, PPS, ABS). In their results, injection molding had a noteworthy impact, so a detailed study of the injection molding process for those parts would be necessary to improve the precision of that study, as injected parts were assessed with the injection molding dataset of EcoInvent. The authors already warned that the impacts of the injection molding process are high due to the presence of solvents in the EcoInvent dataset, which specially influences the results of the ozone layer depletion. Some other examples of studies where EcoInvent's injection molding dataset is used are LCAs of agricultural machinery (Bortolini, et al., 2014), road lighting luminaires (Tähkämö & Halonen, 2015) and fuel cells (Cox & Treye, 2015). The injection molding process should be studied in detail and measured in all LCA studies where plastic components are a significant part of the product.

5. Conclusions

Throughout this study, the environmental impact of the injection molding process has been analyzed. A methodology and experimental measurement procedure have been explained and applied to a wide range of HDPE plastic parts.
The generic EcoInvent dataset (EcoI) and our adapted case to analyze the injection molding of conventional plastics (CEcoIPP) yield similar environmental burdens.
Finally, the measured parts' environmental results exhibited significant differences.

This is due to electricity consumption differences, ranging from 0,43 kWh/kg to 2,3 kWh/kg.

To properly assess the actual environmental impact of a specific injection molding process, the real electricity consumption of it must be measured. Otherwise, the results would be quite far from the real values.

6. Future directions of research

Additionally, this paper opens a future direction of research, investigating how the electricity consumption of the injection molding machine can be optimized by means of a better machine selection. Additionally, differences between materials and the influence of the part characteristics could be assessed.

Electricity consumption should be used as a selection criterion of injection molding machines to develop a more environmentally conscious way of manufacturing injected plastic parts and simultaneously reducing production costs.

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Figure captions

Figure 1: Methodology steps performed to obtain the CEcoIPP dataset
Figure 2: Final Dataset
Figure 3: System Boundaries of our particularized injection molding process
Figure 4: Parts for which the processing has been measured
Figure 5: 78400-kN Injection Molding Machine A
Figure 6: 29400-kN Injection Molding Machine C
Figure 7: 833-kN All-electric Injection Molding Machine G
Figure 8: Measurement equipment
Figure 9: Impact results for each impact category (EcoI)
Figure 10: Comparison between CEcoIPP and the measured parts for every impact category and for electricity consumption

Table captions

Description	EcoInvent v3.01 dataset	Customized EcoInvent based PP injection molding process values (CEcoIPP)
Lubricants	Lubricating oil {GLO}| market for | Alloc Def, U	1,67E-05 kg
Water for cooling	Water, cooling, unspecified natural origin	1,11E-02 m^3
Electricity	Electricity, medium voltage market for | Alloc Def, U	2,096 kWh
Plastic waste	Waste plastic, mixture {GLO}| market for | Alloc Def, U	0,005 kg
Infrastructure	Packaging box factory {GLO}| market for | Alloc Def, U	1,43E-09 p

Table 1 EcoInvent's Dataset, used to particularize the case

Injection Molding Machine	**Clamping Force [kN]**	**Injected Part #**	**Type**
A	78400	1	Hybrid
B	50960	2	Hybrid
C	29400	3	Hybrid
D	11760	4	Hybrid
E	7350	5 and 6	Hybrid
F	3920	7	Hybrid
G	833	8	All-electric

Table 2: Injection molding machines in which parts have been injected

Part #	Weigh injected per cycle [g]	Cycle time [s]	Electricity Consumption [kWh/kg]
1	71800	216,0	0,4310
2	30300	147,0	0,7878
3	10500	175,0	0,8832
4	1253	81,0	0,9005
5	260	42,9	2,3007
6	836	40,0	0,7088
7	100	44,4	1,8699
8	15	15,0	0,6101

Table 3: Data of the measured parts

Impact category	**Unit**	**Environmental Impact per kg of processed material**
Abiotic depletion	kg Sb eq	1,428E-06
Abiotic depletion (fossil fuels)	MJ	1,887E+01
Global warming (GWP100a)	kg CO2 eq	1,094E+00
Ozone layer depletion (ODP)	kg CFC-11 eq	1,254E-07
Human toxicity	kg 1,4-DB eq	3,768E-01
Fresh water aquatic ecotox.	kg 1,4-DB eq	4,197E-01
Marine aquatic ecotoxicity	kg 1,4-DB eq	1,333E+03
Terrestrial ecotoxicity	kg 1,4-DB eq	2,537E-03
Photochemical oxidation	kg C2H4 eq	2,940E-04
Acidification	kg SO2 eq	4,545E-03
Eutrophication	kg PO4--- eq	2,250E-03

Table 4: EcoInvent v3.01 (EcoI) results

Impact category	Unit	Environmental Impact per kg of processed material	% Electricity
Abiotic depletion	kg Sb eq	1,10E-06	43,02%
Abiotic depletion (fossil fuels)	MJ	1,63E+01	99,37%
Global warming (GWP100a)	kg CO2 eq	1,09E+00	98,17%
Ozone layer depletion (ODP)	kg CFC-11 eq	1,15E-07	99,64%
Human toxicity	kg 1,4-DB eq	4,20E-01	94,91%
Fresh water aquatic ecotox.	kg 1,4-DB eq	5,37E-01	97,83%
Marine aquatic ecotoxicity	kg 1,4-DB eq	1,70E+03	98,58%
Terrestrial ecotoxicity	kg 1,4-DB eq	3,45E-03	99,53%
Photochemical oxidation	kg C2H4 eq	2,06E-04	98,38%
Acidification	kg SO2 eq	4,78E-03	98,69%
Eutrophication	kg PO4--- eq	2,89E-03	99,31%

Table 5: Particularized case (CEcoIPP) results

Impact category	EcoI	CEcoIPP
Abiotic depletion	100,0%	77,0%
Abiotic depletion (fossil fuels)	100,0%	86,4%
Global warming (GWP100a)	100,0%	99,6%
Ozone layer depletion (ODP)	100,0%	91,7%
Human toxicity	100,0%	111,5%
Fresh water aquatic ecotox.	100,0%	127,9%
Marine aquatic ecotoxicity	100,0%	127,5%
Terrestrial ecotoxicity	100,0%	136,0%
Photochemical oxidation	100,0%	70,1%
Acidification	100,0%	105,2%
Eutrophication	100,0%	128,4%

Table 6: Comparison between the EcoI and CEcoIPP results

Impact category	**CEcoIPP**	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**	**#8**
Abiotic depletion	100,0%	65,5%	72,8%	74,8%	75,1%	103,7%	71,2%	94,9%	69,2%
Abiotic depletion (fossil fuels)	100,0%	21,1%	38,1%	42,6%	43,4%	110,0%	34,3%	89,5%	29,6%
Global warming (GWP100a)	100,0%	22,1%	38,8%	43,3%	44,1%	109,7%	35,1%	89,5%	30,5%
Ozone layer depletion (ODP)	100,0%	20,9%	37,9%	42,5%	43,3%	110,1%	34,2%	89,6%	29,5%
Human toxicity	100,0%	24,6%	40,8%	45,1%	45,9%	109,3%	37,2%	89,8%	32,7%
Fresh water aquatic ecotox.	100,0%	22,3%	39,0%	43,4%	44,2%	109,6%	35,3%	89,5%	30,7%
Marine aquatic ecotoxicity	100,0%	21,7%	38,4%	42,9%	43,7%	109,4%	34,7%	89,2%	30,1%
Terrestrial ecotoxicity	100,0%	20,9%	37,9%	42,4%	43,2%	109,7%	34,1%	89,3%	29,4%
Photochemical oxidation	100,0%	21,8%	38,6%	43,0%	43,9%	109,5%	34,9%	89,3%	30,2%
Acidification	100,0%	21,6%	38,4%	42,9%	43,8%	109,7%	34,7%	89,4%	30,1%
Eutrophication	100,0%	21,1%	38,0%	42,6%	43,4%	109,7%	34,3%	89,3%	29,6%

Table 7: Results comparison

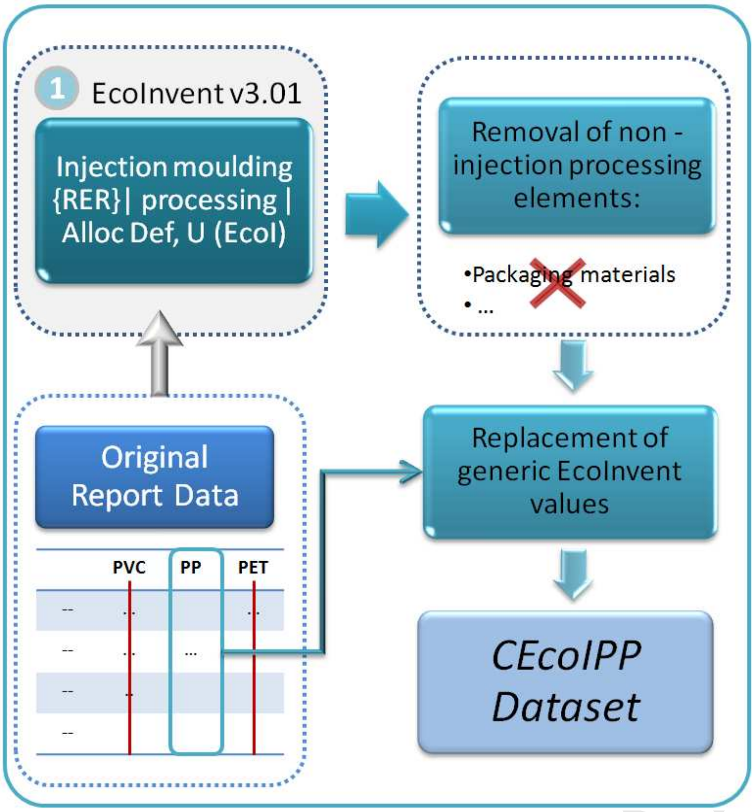

Figure 1: Methodology steps performed to obtain CEcoIPP dataset

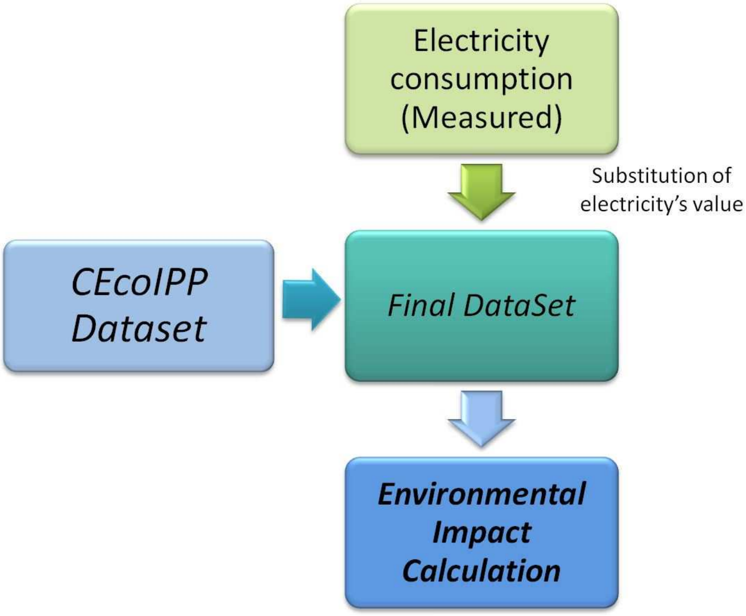

Figure 2: Final Dataset

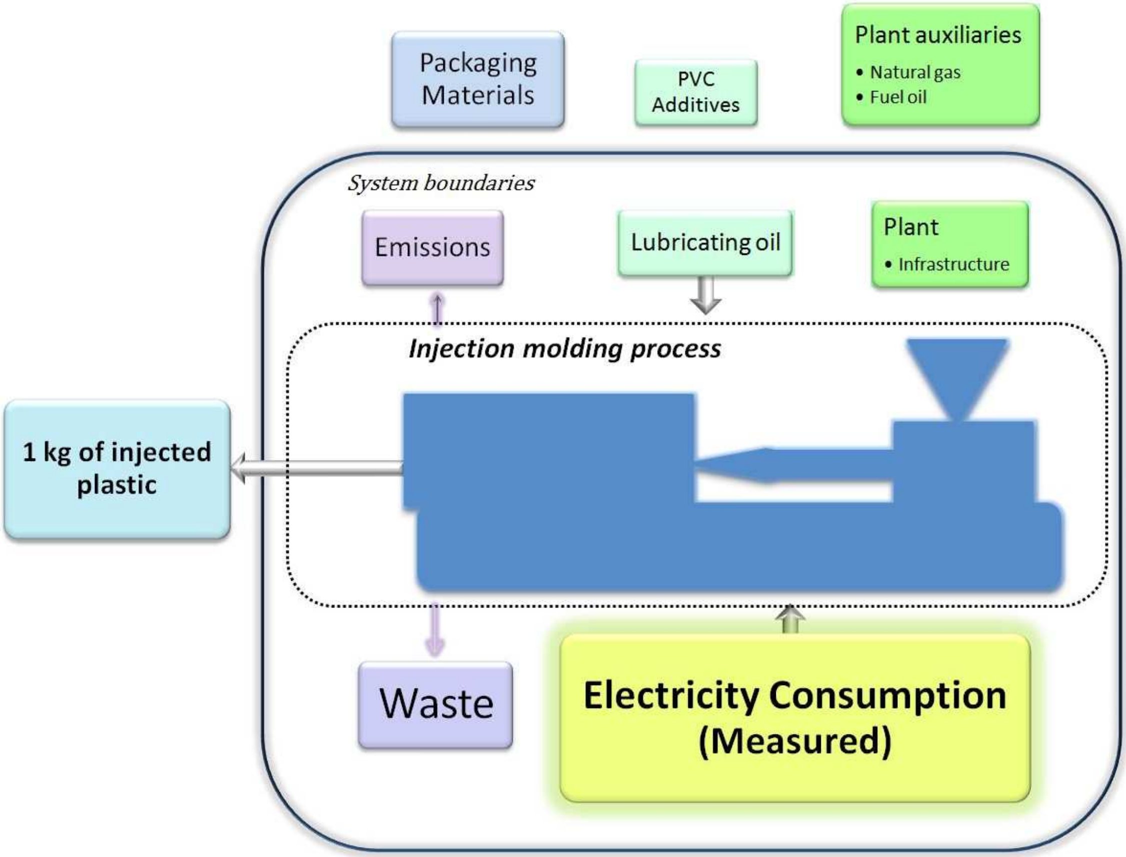

Figure 3: System Boundaries of our particularized injection molding process

Figure 4: Parts for which the processing has been measured

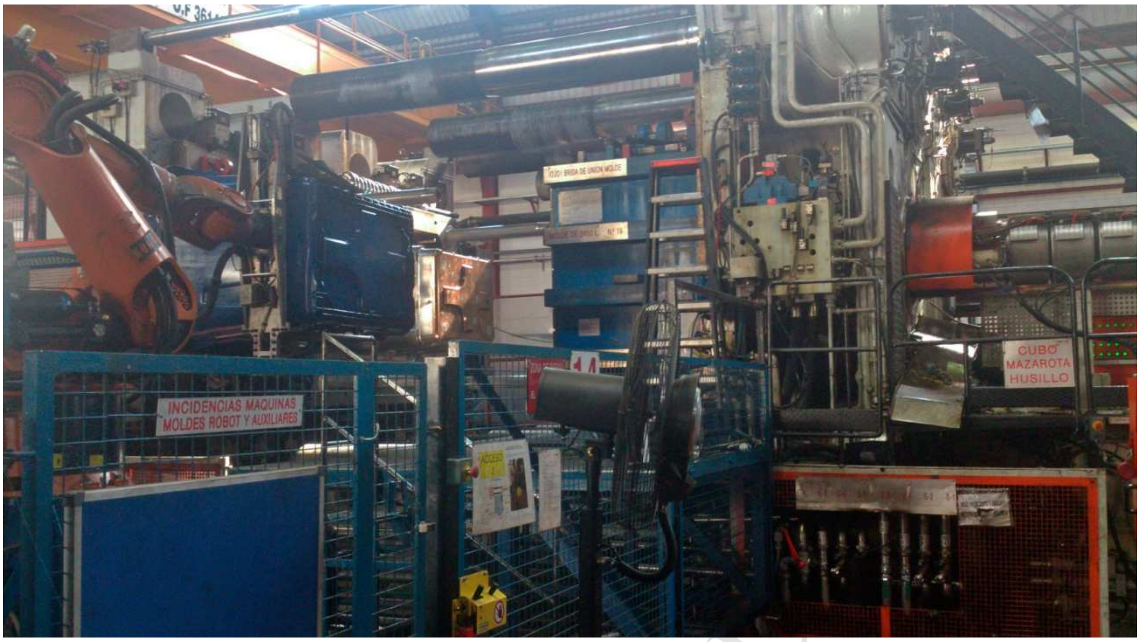

Figure 5: 78400-kN Injection Molding Machine A

Figure 6: 29400-kN Injection Molding Machine C

Figure 7: 833-kN All-electric Injection Molding Machine G

Figure 8: Measurement equipment

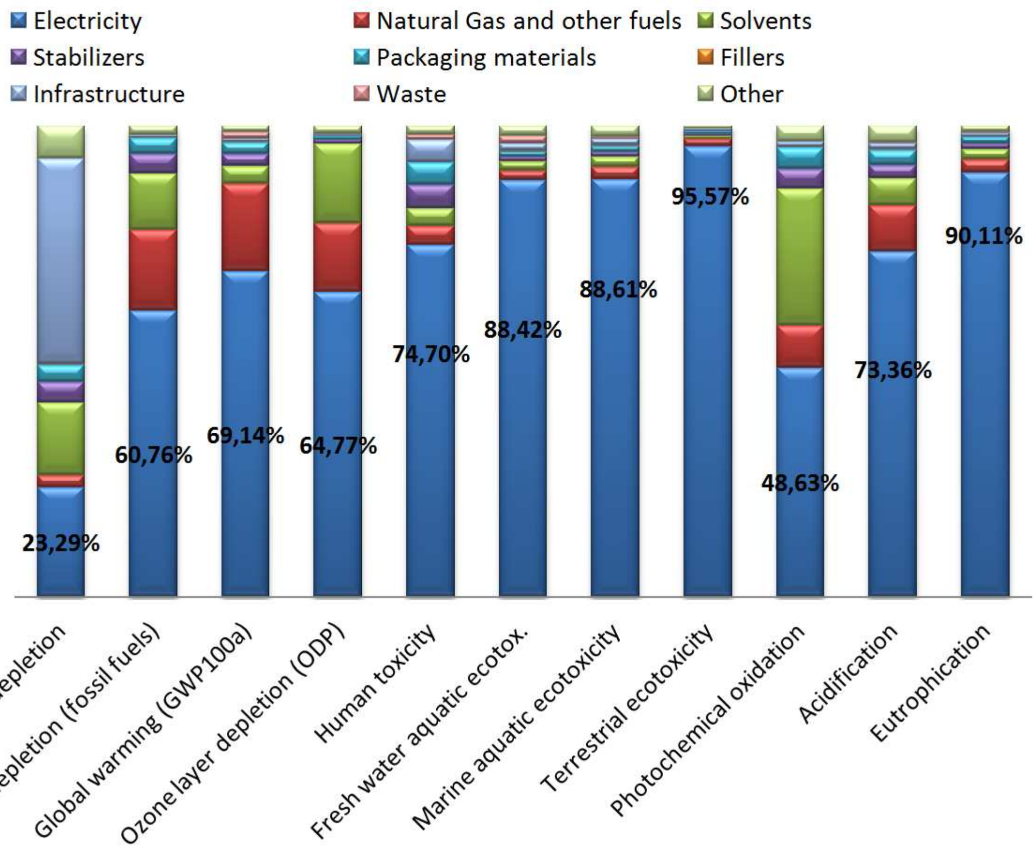

Figure 9: Impact results for each impact category (EcoI)

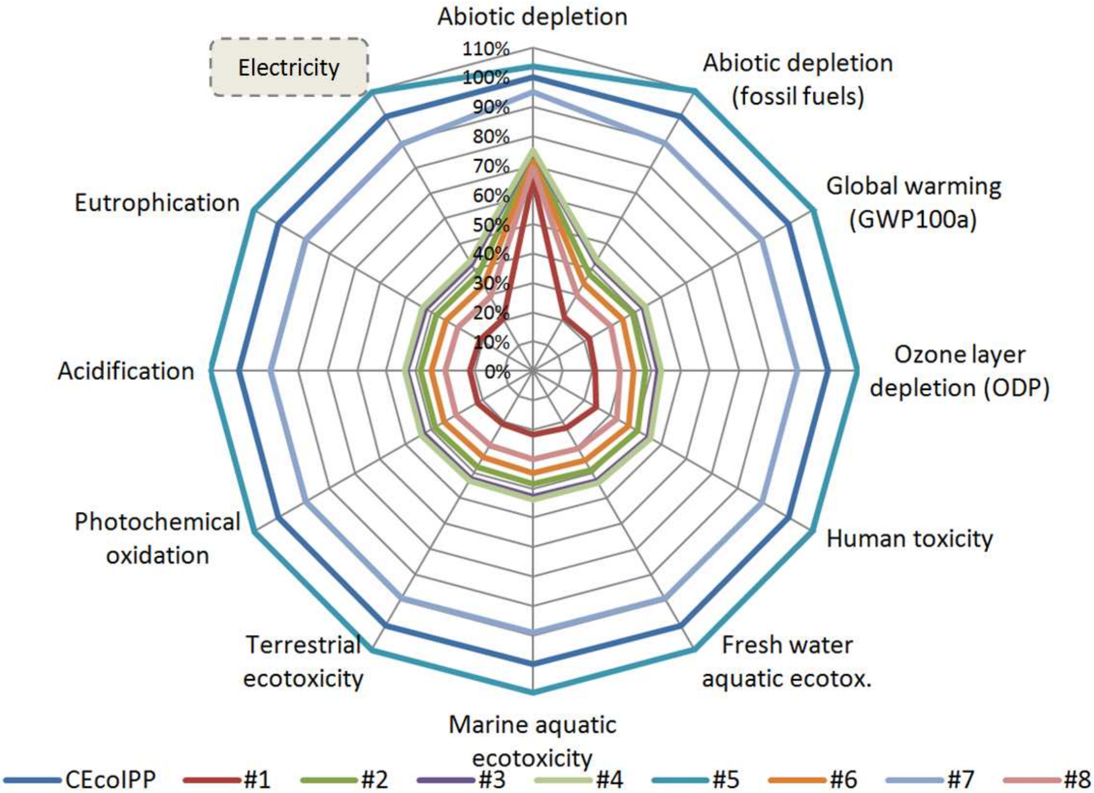

Figure 10: Comparison between CEcoIPP and the measured parts for every impact category and for electricity consumption

- A LCA of the injection molding process applied to HDPE parts has been carried out.
- Electricity consumption is the most relevant factor in terms of environmental impact.
- Electricity consumption measurements show great variations depending on machines used.
- Electricity consumption should be used as selection criterion of injection molding machines.