LCA SOFTWARE FOR ENVIRONMENTAL IMPACT ASSESMENT OF INJECTED MOULDED PLASTIC PARTS

Ana Elduque[(a)], Daniel Elduque[(b)], Carmelo Pina[(c)], Carlos Javierre[(d)], Ángel Fernández[(e)]

[(a),(b),(d), (e)] Department of Mechanical Engineering, University of Zaragoza, C/María de Luna, 3, 50018 Zaragoza, Spain
[(c)] BSH Electrodomésticos España, S.A., Avda de la Industria, 49, Zaragoza (Spain)

[(a)] aelduque@unizar.es,[(b)] delduque@unizar.es, [(c)] carmelo.pina@bshg.com [(d)] carlos.javierre@unizar.es, [(d)] angel.fernandez@unizar.es

ABSTRACT
A software for the simulation of the environmental impact of injected moulded plastic parts is presented in this paper. The LCA model and assumptions made for calculations are explained, and the software's interface is shown. A case study is carried out in order to provide a clearer explanation of the applicability of this environmental impact simulation software. Results show how the raw material is the most influential factor. In second position is the injection moulding process, which has been modelled in detail, depending on many parameters.

Keywords: environmental impact simulation, software, life cycle assessment, injection moulding

1. INTRODUCTION

A more environmental benign manufacturing is an important goal for all industrial companies nowadays. As pointed out by (Duflou et al. 2012), a more demanding environmental legislation (European Parliament 2009), achieving cost savings thanks to more efficient technologies, or competitive advantages, should be important reasons to motivate a movement towards sustainability.

During the last decades, simulation tools have been developed in order to evaluate the environmental performance of products and processes. One of the most important methodologies to achieve that is the Life Cycle Assessment. There are numerous examples of this methodology where the environmental performance of different kind of products or processes is simulated. Studies like the ones performed by (Martínez et al. 2009), (Cellura et al. 2012), (Ribeiro et al. 2013a), (Jiménez et al. 2014), (Elduque et al. 2014b), (Tsiropoulos et al. 2015), (Martínez et al. 2015), (Wäger and Hischier 2015) and (Simon et al. 2015) are some examples of them.

Plastics manufacturing is one of the most important industrial manufacturing processes worldwide.

Several authors have analyzed this process, trying to improve its efficiency by means of design of experiments (Packianather et al. 2013) or software simulation. Also calculating its environmental impact in detail is an issue that is being addressed in other researches (Elduque et al. 2015).

In this paper a software simulation tool to perform the LCA of an injected moulded part is presented.

When a LCA is carried out, all the life stages of the product have to be taken into account in the model. Thereby, the production of the polymer, distribution of the raw material to the manufacturing company, the usage of auxiliary equipment and the injection moulding process itself should be included in the simulation. Also packaging materials used to deliver the product to the client, its distribution and its end-of life should be considered, as well as the waste generated throughout the life cycle, (Figure 1).

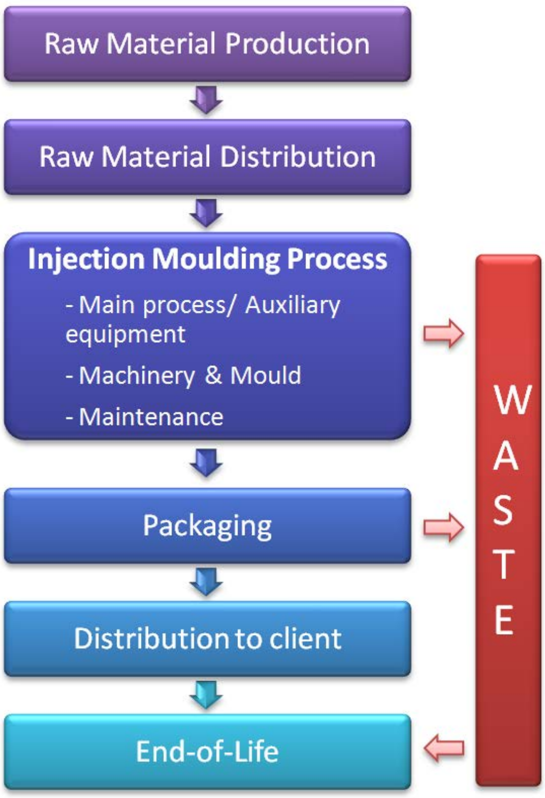

Figure 1: Life Cycle Stages of an Injected Moulded Part

This is a relevant research topic as a wide range of authors have analyzed the energy efficiency of this process to reduce it (Gutowski et al. 2006), (Borchardt et al. 2011), (Huang and Yang 2012), (Madan et al. 2014), (Müller et al. 2014), (Spiering et al. 2015) whereas others have analyzed the Life Cycle Cost of injection moulding (Ribeiro et al. 2013b). Also, several researchers have tried to reduce the impact of plastic parts (Lucchetta and Bariani 2010), (Park et al. 2013).
Simulations tools have been widely used to improve injection moulding (Gerber et al. 2006), (Aisa et al. 2006), (Jimenez et al. 2009), (Fernandez et al. 2013).
A streamlined environmental impact simulation tool based on an a LCA model, that takes into account all the relevant factors related to the process of manufacturing an injected moulded plastic part, is presented in this paper.

2. SOFTWARE DEVELOPMENT AND LCA MODELLING IMPLEMENTATION

This LCA software has been developed using Visual Basic .NET having a very clear structure. It has three main blocks: databases used as inputs to the environmental impact simulation model, user interface, where input data are introduced by the user throughout several screens to characterize the studied part and results are displayed and, at last, the software's code which acts as a black box for the user. The input data are processed, saving it in variables, which interoperate and return the simulation results that are then displayed in the interface.
In subsection 2.2, the program's screens are going to be described as well as the internal assumptions that are behind them to simulate the environmental impact of the considered blocks.
In order to help the user during the data introduction, multiple guides and suggestions are included in the software's interface.

2.1. Databases

In order to simulate the environmental impact results of an injected moulded plastic part, several databases have been developed. One of them contains the inventory datasets and their environmental impact calculated in mPt (ReCiPe Methodology) and kilograms of CO_2 eq. Aspects like the electric mix, lubricating oil, materials such as polymers for the injection moulding, metals for the mould, packaging materials...etc. are included. These values have been obtained from EcoInvent database.
Other databases contain properties of materials, or data related to required equipment for the process that the program uses, for example, to simulate the energy consumption.

2.2. Software Methodology

Software interface is divided into different screens where required data can be introduced by the user or selected between different modelling options provided by the software.

A summarized flux diagram of the software is shown in Figure 2.

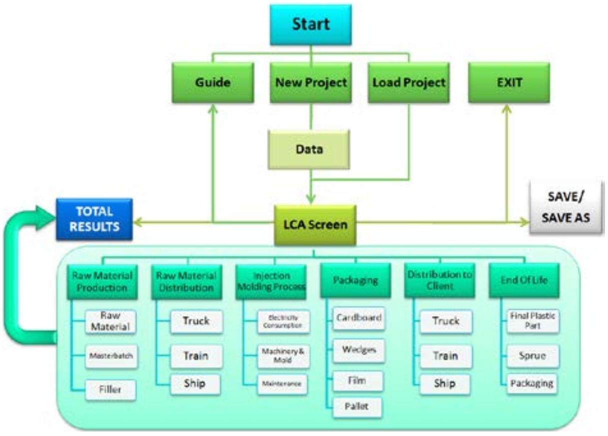

Figure 2: Software's Flux Diagram

Data regarding the part's net weight, the mould's feeding system and the number of the mould's cavities are required at the start of the modelling case study, in order to determine the quantity of sprue associated with the final part.This sprue could be assessed separately at the end-of-life phase. For example a mould without cold runners and one cavity hasn't got any sprue, but a plastic part obtained from a multy-cavity mould with a cold runner feeding system, will have associated the proportion of the runner also as used material. In addition, the total of kilograms injected to obtain the moulded part are calculated, as the section of the injection molding process simulates the environmental impact per processed kilogram.
Figure 3 shows the main LCA screen of the program which allows to go to the input data screen of each phase of the plastic part's life cycle.

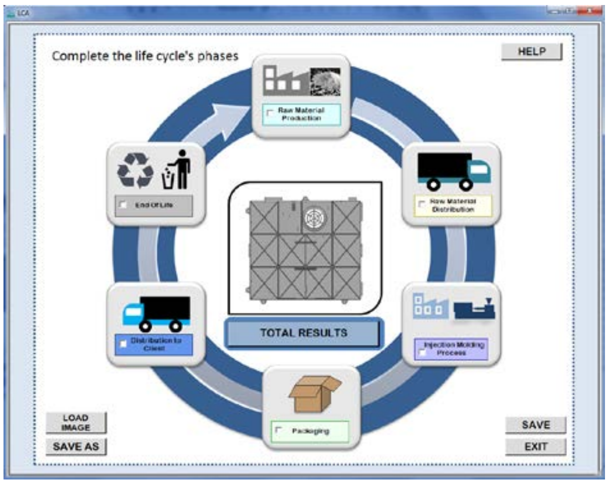

Figure 3: Software's LCA Screen

Environmental impact results are displayed in each section to check how the input data affect the results but also a "Total Results" screen has been developed to compare which life cycle phases have more importance in the ReCiPe Methodology and the carbon footprint (kg CO_2 equivalent).

2.2.1. Raw Material Production

The first phase of the LCA model for an injected moulded part is the raw material production. The database provides the environmental impact of materials obtained from professional Life Cycle Inventory databases such as EcoInvent. In addition, if the user wants to incorporate a new raw material, a mix of thermoplastic polymer, masterbatch and fillers can be modelled to better evaluate the environmental impact of the part's material.

2.2.2. Raw Material Distribution

The raw material is then distributed to the conversion's factory. A transport route can be configured using either road, rail or marine transport. The environmental impact's unit for this section is kg.km and the transported weight corresponds to the part's gross weight. An extra weight can be added if sacks or boxes are considered for the modelling of this phase.

2.2.3. Injection Moulding Process

The most important part of the program is the section where the environmental impact of the process is modelled.

Energy consumption is simulated as a sum of individual electric consumptions like the heating of the barrel, the hot runners if they are used, pneumatic or conveyor systems, dryers, coolers, and the drivers of the injection moulding machine. If known, it is possible to introduce experimental power measurements of the machine, in order to have a more precise model and therefore more adequate simulation results (Figure 4).

If it is not possible to introduce experimental measurements, a simulation of the energy consumption can be done. Energy consumption is modelled as a sum of six blocks:

- Plastification: the required energy is approximated as the specific heat of the thermoplastic material multiplied by the difference between injection temperature and factory's temperature, and divided by an assumed barrel's yield value.
- Hot runner: two options have been considered for the model. First one is to consider its energy consumption as a percentage of the plastification phase. The other one provides a power value (in kW) of typical equipment and a usage factor that usually is 50% (Thiriez 2006).
- Conveying system: manufacturer's specifications from several equipments of different power's level are provided. The user can select between different modelling options and indicate if the equipment's working point is optimum, in average load or over-sized. A value of consumption is returned depending on the selection. This value was obtained as an arithmetic mean of the different working points.

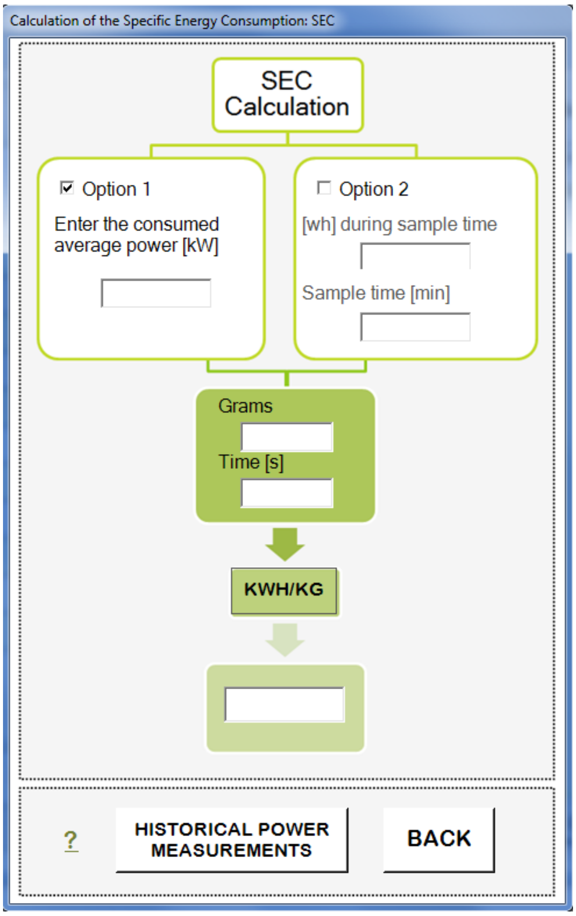

Figure 4: Specific Energy Consumption Calculator

- Dryer: as in other phases two alternatives can be selected for the model. Values of kWh/kg needed by material are provided (Thiriez 2006). Also the energy consumption in kWh/kg can be determined by introducing the dryer's power and the kilograms to be dried. A typical drying time for the material is suggested by the program's database.
- Refrigeration: cooling of the mould is simulated as the specific heat of the part's material multiplied by the difference between the injection and ejection temperature, and divided by a coefficient of performance. The oil hydraulic's cooling is of great importance as well, due to the oil's temperature has to be maintained stable to assure a good performance. The kWh/kg required is modelled with a lineal correlation obtained from specifications of a chiller's manufacturer.
- Drivers: the energy requirements for mould clamping (opening and closure) and the extruder are incorporated to the model.

In addition to the electricity consumption, the machinery and the mould, needed to manufacture the plastic part, have to be included as well in the model.

Therefore the environmental impacts of metals like steel, aluminium or copper, which are part of the mould, are also assessed. They contribute to the final results proportionally, as a function of the quantity of parts produced with each one (Figure 5 and Figure 6). Its end of life scenario is also included, providing suggestions of percentage for recycling and landfilling.

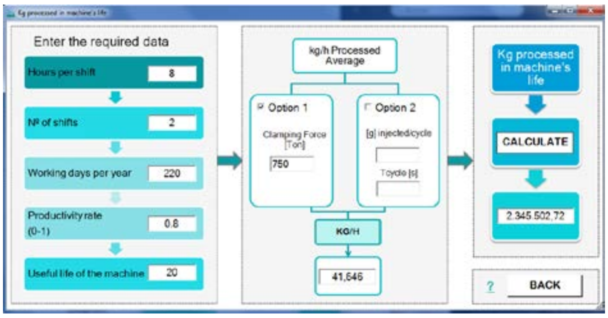

Figure 5: Production in the Injection Machine's Life

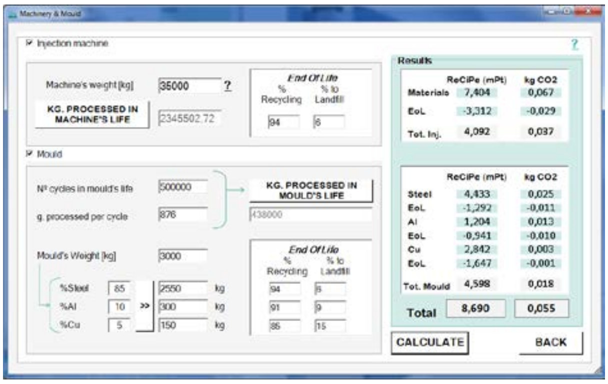

Figure 6: Environmental Impact Calculation of the Mould and the Injection Machine

The maintenance of the machine is also considered in the LCA model. The capacity of the oil tank has to be introduced along with the work hours between changes of the hydraulic oil in order to evaluate the environmental impact of the machine's maintenance. The environmental burden of the tank's oil has to be divided between all the kilograms injected during the time that has been used.

2.2.4. Packaging

Packaging materials like corrugated cardboard, expanded polystyrene, or plastic film, made for example of polyethylene, can be considered in this section. These three materials constitute a box in which one or several parts can be packaged. Also pallets can be introduced as a part of the packaging, dividing its environmental impact between the number of parts per pallet. As some of these packaging materials might be reused, a number of uses can also be assigned for pallets, wedges and cardboard to properly assess its environmental impact.
Giving the main dimensions of the part, an estimation of the packaging material needed can be done in a help's screen, taking into account the volume of the part.

2.2.5. Distribution to Client

Similarly to the raw material distribution, the transportation of the manufactured plastic part is taken into account in our model. Two different routes can be configured in order to give flexibility to the introduction of data.
Different scenarios can be simulated, for example if the plastic part is manufactured in a different factory than the assembly's factory. In both routes the user has to indicate the weight to be considered, net part's weight with or without the packaging weight.

2.2.6. End- of- Life

In this last phase, an end of life scenario is assigned for both the part and its sprue and the packaging materials, considering percentages of recycling, incineration or landfilling.
The percentage values suggested are from the technical report IEC TR62635 (IEC 2012), but they can be changed by the user if it is convenient to do so.
The sprue from the injection moulding process can be treated as the final part, or regrinded if it is reused in the same factory to inject another plastic part. If this alternative is selected, the environmental impact of this material will be subtracted from the total results. An electricity consumption value for the regrind process will be considered instead.
The end-of-life scenario for the packaging materials is also included in the LCA model, using values from Eurostat (Eurostat 2015).

3. CASE STUDY

In order to provide a clearer explanation of how the program works and give some quantitative results, an application example is going to be shown.

3.1. Part's Data

The plastic part that is going to be studied is a housing of an induction hob as the one analyzed by (Elduque et al. 2014a). Its function is to fix the electronic boards of the induction hob as well as closing the assembly. This plastic part is made of polyamide reinforced with glass fibre (PA66 GF30). It has a weight of 876 grams and its main dimensions are 460x415x40 mm (Figure 7).

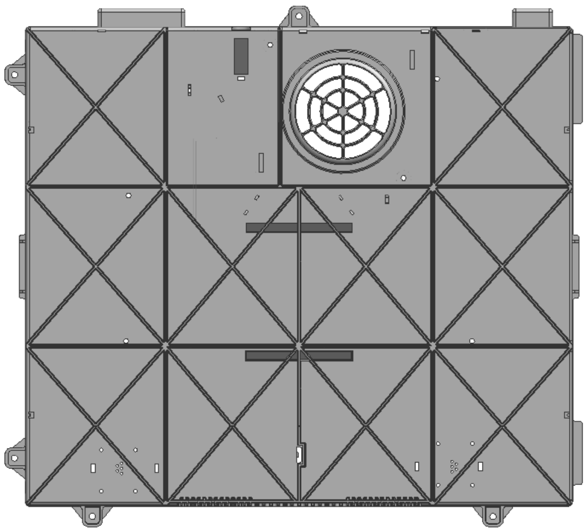
Figure 7: 3D Model of the Case Study Part

Its mould has only one cavity, and it has not got cold runners (Figure 8). This plastic part is injected in an injection moulding machine of 750 tons of clamping force.

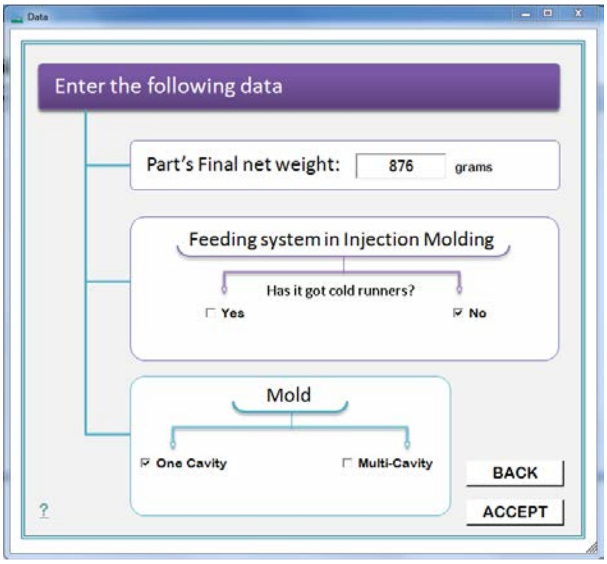

Figure 8: Data Required at the Start of the Modelling Case Study

3.2. Raw Material

Figure 9 shows the software's screen where the raw material is selected. For this case the "Nylon 6-6, glass-filled (RER) production" EcoInvent dataset was selected as the 100% of raw material. This thermoplastic has a high environmental impact in both studied categories. (522,6 mPt/part and 6,17 kg of CO_2 eq./part).

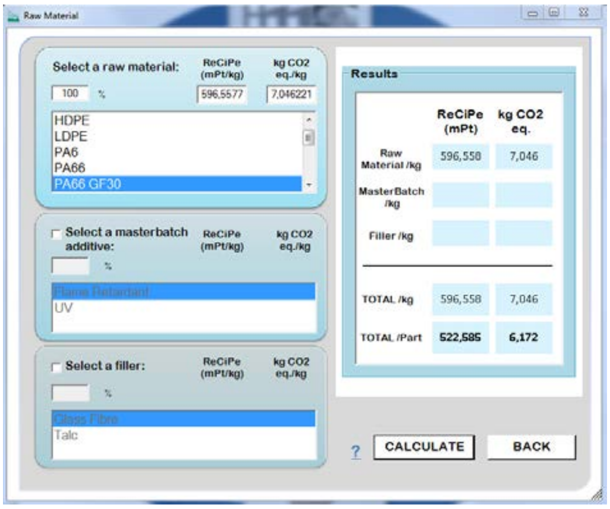

Figure 9: Selection of the Raw Material

3.3. Raw Material Distribution

A distance of three hundred kilometres is introduced to distribute the raw material to the factory by a >32 ton EURO 5 truck where the part is going to be manufactured. (Figure 10).

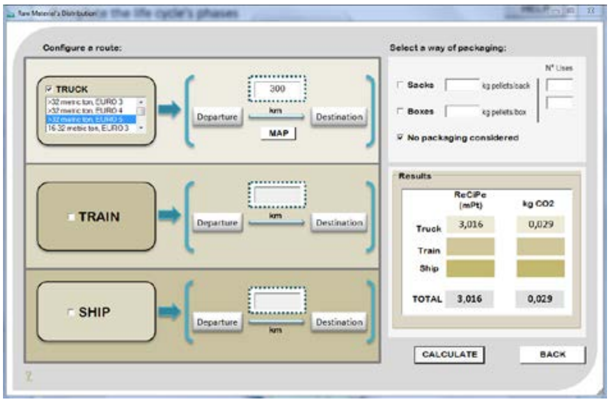

Figure 10: Raw Material's Distribution

3.4. Injection Moulding Process

To simulate the environmental impact of this phase, three subsections have to be completed. The most important one, as the results will show, is the electricity consumption. Figure 11 indicates the introduced data for the plastification phase, where the injection temperature is 300 ºC.

Also the consumption of the hot runner is estimated considering an equipment of 5.35 kW and a usage factor of 50%.

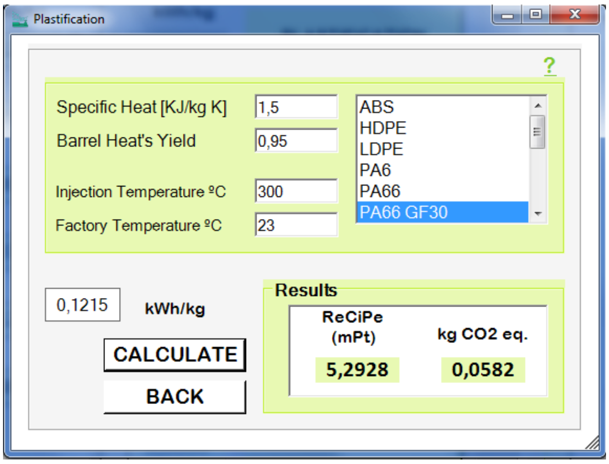

Figure 11: Modelling of the Plastification Phase

Using the program's help, a 2.2 kW power for the conveying system is selected, which for this case is an optimum working point taking into account the kg/h required by the manufacturing process (Figure 12).

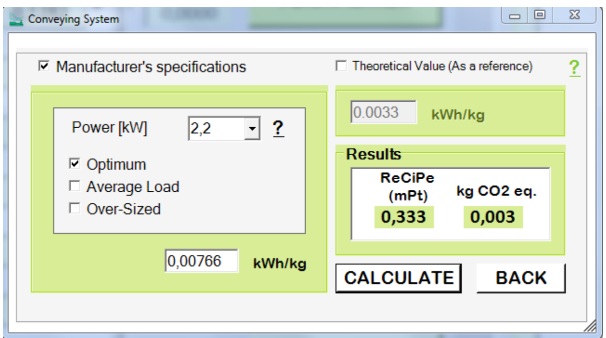

Figure 12: Modelling of the Conveying System

The raw material of this part (PA66) requires a drying process. A reference value of electricity consumption of 0.07 kWh/kg extracted from the literature is selected. The oil's cooling is considered in the refrigeration block considering the size of the injection machine.
Given that this component is manufactured in Spain, a Spanish electric mix is selected for this model. In Figure 13, the main screen for the electricity consumption collects the results of this section.

Figure 13: Modelling of the Electricity Consumption

An electricity consumption of 0,786 kWh/kg is obtained which is considered as an acceptable estimation, as this value is only a five percent higher than the one registered by the power measurement equipment (Elduque et al. 2014a).
It is worth noting that the plastification phase and the drivers of the injection moulding machine represents almost the 70% of the electricity consumption.
The second subsection to evaluate this manufacturing process is the Machinery & Mould. The injection moulding machine weights 35000 kilograms. As previously showed in Figure 5, a calculation of the kilograms produced during the useful life of the machine is used to evaluate its impact.
In addition the environmental impact of the 3000 kg-mould is divided between the total of kilograms processed in the mould's life, considering 500000 cycles (Figure 6). An end of life scenario is assigned for the steel, copper, and aluminium belonging to the injection machine and the mould. Also the hydraulic oil consumption is calculated (Figure 14).

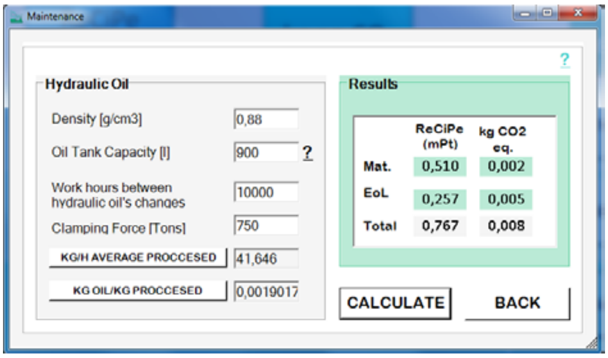

Figure 14: Maintenance for the Injection Moulding Process

The final results of the injection moulding process phase, are obtained by processed kilogram, therefore, in the total results this value will be multiplied by the part's gross weight (0.876 kg).
As it can be seen in Figure 15, the electricity consumption is the most influential factor in the environmental impact of the injection moulding process (nearly 80% of the impact simulation results for the ReCiPe methodology and almost 86% for the carbon footprint).

Figure 15:Results for the Injection Moulding Process

3.5. Packaging

The packaging required to distribute the manufactured part to the assembly plant is estimated as the next figure shows (Figure 16).

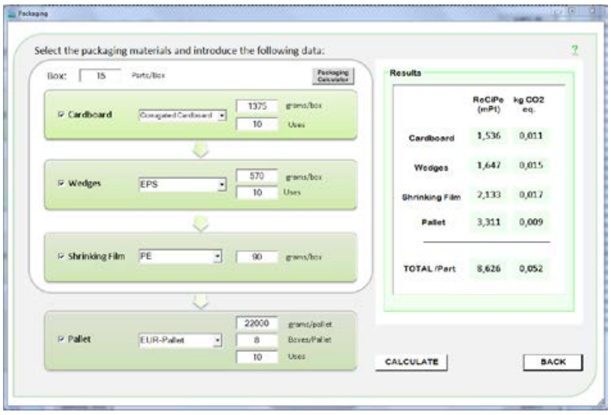

Figure 16: Packaging Materials Selected for the Case Study

3.6. Distribution

For this case study, two different routes are configured. The first one of 35 kilometres covers the distance between the injection factory and assembly's factory where this part will be assembled to the induction hob. The weight of the packaging materials is added to the part's weight for this calculation.
In addition, it is going to be considered the final distribution of this part to client, in order to observe the influence in the distribution's phase of the weight of this part. To achieve this, a total of 1800 kilometres by truck are considered (Pina et al. 2015).
For both routes a >32 ton EURO 5 truck is considered, using EcoInvent's dataset (Figure 17).

Figure 17: Distribution to Client

3.7. End of Life

As the material of this part is a reinforced thermoplastic, it is considered as not suitable for direct recycling and it is all sent to landfill, increasing the environmental impact of the material in 8,4 mPt/part, and 0,08 kg CO_2 eq./part. The end of life scenario for the packaging materials is included as well, as is indicated in Figure 18.

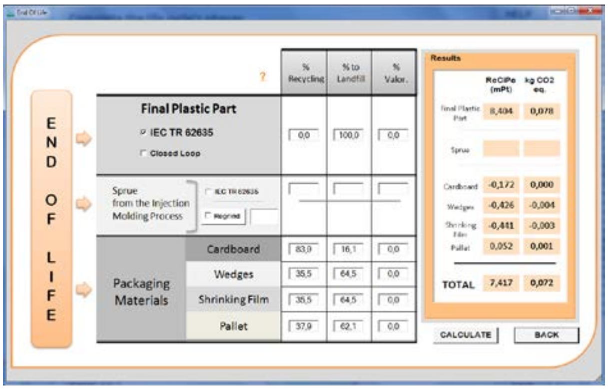

Figure 18: End-of-Life Scenarios

3.8. Results

Figure 19 summarizes the final results of this case study. The environmental impact of the polyamide is quite high in comparison with other thermoplastics. This causes that more than the 85% of the environmental impact for both categories is due to the raw material production. Nevertheless the manufacturing process contributes with more than 6% to the total results.

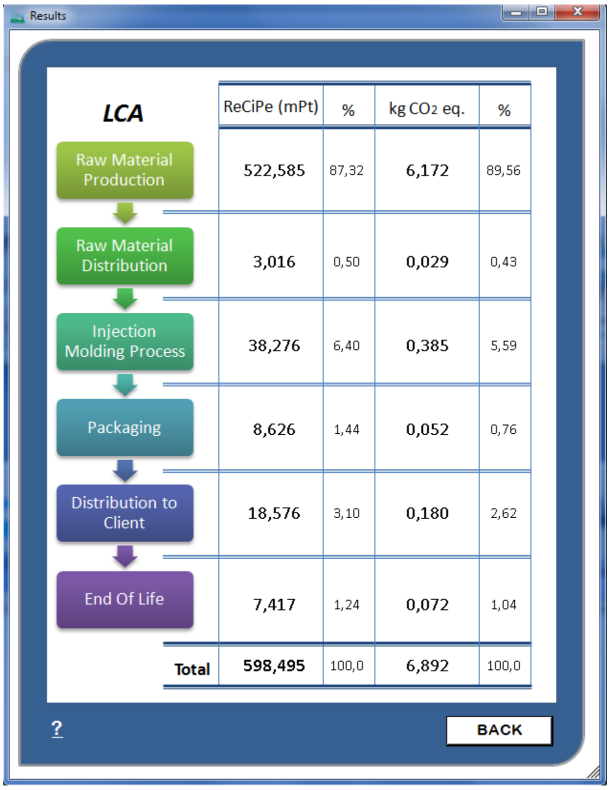

Figure 19: Total Results of the Case Study

4. CONCLUSIONS

The software shown in this paper simulates the environmental impact of an injected moulded plastic part by means of a LCA model. The results provided by this program allows designers to evaluate in detail the environmental impact of a specific plastic part and thereby simulate different alternatives, as the model is sensitive to many different parameters such as the raw material of the studied part, routes and means of transport used for distribution, the characteristics of the mould or the injection moulding machine that define the manufacturing process, or several end of life scenarios to complete the life cycle analysis simulation.

Results from the case study and other studied parts by the authors have shown that usually the most important phase, due to its higher environmental impact, is the production of the raw material but also the second one which has a remarkable importance is the manufacturing process, depending on many factors on which designers or engineers have influence.

Having this simulation tool implemented, our future work would be to relate these simulations of the harm caused to the environment, with the economic cost of the part's manufacturing. The modelling and simulation performed by this software would allow companies to evaluate in a two dimensional way the sustainability of their products. In addition, several alternatives could be compared, letting the engineer choose the most favourable case, achieving impact`s reductions from an economic and environmental standpoint.

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