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Influence of material and injection molding machine's selection on the electricity consumption and environmental impact of the injection molding process: an experimental approach

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Reducing energy consumption is an important issue for green manufacturing. In this paper, the specific energy consumption (SEC) of the injection molding process is analyzed. Results showed significant variations depending on the injected thermoplastic material and the type of injection molding machine (IMM) suggesting that IMM selection has a high relevance for the efficiency, cost and environmental impact of the process. The manufacturing of 36 plastic parts has been characterized by measuring the electricity consumption and obtaining the environmental impact, being this consumption its most important factor. A descending tendency for both is observed when high throughputs are obtained because the size of the IMM is more optimized. Conversely, the savings obtained by the all-electric IMMs are significant. This research could help engineers to properly select an IMM by taking into account the part weight, material and environmental criteria. Also, this study will be useful for life cycle assessment (LCA) practitioners. Real consumption data is presented, providing details about the materials, and relationships with the IMM that was used. The high variability suggests that if the injection molding process is relevant in a LCA study, its consumption must be analyzed in depth, preferably by measuring real consumptions in the factory.

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NOMENCLATURE

ΔT = difference between room and injection temperature
η= percentage of utilization of the IMM's capacity
E_{part} = energy for the production of a plastic part (kWh)
E_{period} = average consumed energy in sampling period (kWh)
E_{plast} = required energy to heat the barrel during plasticizing phase (kWh/kg)
n = number of cavities of the mold
ρ = raw material density (g/cm^3)
SEC = specific energy consumption
s_h = specific heat of thermoplastic (kJ/kg K)
t_c = cycle time (h)
$\tau_{sampling}$ = sampling period (h)
V_{max} = maximum injection volume of the IMM (cm^3)
w= weight injected per cycle (kg)
y= throughput (injected kg/h)

1. Introduction

As climate change and other environmental concerns become more relevant, industries have to deal with the growing pressure to decrease their carbon footprint and their environmental impact. New and more exigent regulations along with an increase in the cost of energy are likely to increase that pressure even more for manufacturing companies.[1]

Methodologies, tools, and databases have been developed over the last decades in the field of industrial ecology in order to assess, in a systematic and scientific way, the environmental footprint of products, processes and services, with the objective of identifying hot spots where actions would be more beneficial. Life Cycle Assessment (LCA) is one of the most developed methodologies that has been applied to calculate the environmental footprint of a wide range of products, processes and services. Wind turbines[2], insulation panels[3], small crafts[4], electronic boards[5], photovoltaic systems[6], etc. are a few examples of the broad range of applications that can be assessed by this methodology by considering all of their life phases and allowing them to evaluate different design alternatives.

Manufacturing management systems conceived that cutting costs, such as implementing lean production, could also reduce the environmental impacts of industrial companies. For instance, the 5S technique (Separating, Setting in order, Shining, Standardizing and Sustaining) improves waste management and cellular manufacturing layouts to increase energy-efficiency.[7]

Several authors have researched the idea of including energy-efficiency criteria in the scheduling of production systems by means of energy consumption estimations on a machine level.[8] In addition to the improvement of the process's efficiency, the cost of production could also be optimized by taking into account the time-of-use variability of the electricity prices.[9]

There are numerous studies that have been published regarding energy consumption, specifically in the machining industry. These studies show several ways to improve the scheduling and energy efficiency to obtain more sustainable production. He et al.[10] take into account the machine tool's selection and the sequence of operations to reduce the energy consumption and achieve a more sustainable process. Mativenga and Rajemi[11], analyze the optimum cutting parameters in order to reduce the energy and carbon footprint of the machining of products. Lee et al.[12] study how to reduce the energy consumption of a machine tool at the component level, modeling the behavior of the system, providing a profile of the use of energy and verifying the model experimentally. Behrendt et al.[13] proposed an energy consumption monitoring procedure to apply to machine tools by defining three different modes of operation: the standby power, the component power (main components: drives, spindles, pumps, etc.) and the machining power. Avram and Xirouchakis[14] studied the electricity consumption of a machine tool system by developing a methodology to estimate it and comparing their results to experimental data.

Kara and Li[15] proposed an empirical model to estimate the electricity consumption of the material removal processes, such as turning and milling. They selected the specific energy consumption (SEC, kWh/kg) as the reference to make comparisons between the processes.

One industry that could benefit from energy efficiency actions is the plastics transformation industry, which is currently of great importance in the global economy.[16]

From commodities plastics, such as polyethylene or polypropylene, to more technical or engineering thermoplastics, such as filled polyamides or polycarbonates, these raw materials are used in many products to fulfill various applications with the injection molding process being the most common way of manufacturing them. By measuring the energy demand of these production processes, the electricity consumption can be assessed and actions to improve the process' efficiency can be studied. Deng et al.[17] applied these ideas to the polymer extrusion process by using a power meter to record the energy demand of the process.

Similarly, Spiering et al.[18] performed an energy efficiency benchmark of the injection molding process highlighting the fact that, unlike the environmental impact assessment of the use phase of a product, which is usually studied in depth, the manufacturing phase does not usually have detailed Life Cycle Inventory data and the potential to recognize areas of improvement is very low. The high importance that the electricity consumption has on the environmental impact of the plastic injection molding process was shown in previous research.[19] The environmental impact of this process was also analyzed by applying a calculation methodology to several HDPE plastic parts for which the electricity consumptions were measured during the production conditions. A high variability in the energy process demand depending on the injection molding machine (IMM) and the characteristics of the part and process was observed in this study.[20]

In general, there is still a margin for improvements in the manufacturing industry, as Uluer et al.[21] noted in a case study performed in a home appliances factory. Some actions that enterprises should carry out are monitoring energy consumption and analyzing possible relationships between the consumptions and the manufactured products.

These actions would allow for identifying ways to reduce the energy consumption, along with the environmental and economic impact of the industrial activity.

Following this idea, in this paper an experimental study of the electrical consumption of the injection molding process at the machine level is carried out. The results of the electricity consumption from a total of 36 case studies during the production of different plastic parts made from several kinds of thermoplastics and injected in different IMMs are collected.

These measurements can also be used to assess the environmental impact of the manufacturing of injected plastic parts. Using a methodology previously published by the authors [20], the environmental impact for the injection molding process will also be calculated for the studied parts.

In the following section, a state of art review focusing on the injection molding process will be carried out. The “Materials and Methods” section will cover the details of the required equipment used during this research such as the measurement equipment and procedure, the analyzed IMMs and the plastic parts. Additionally, the methodology used for the calculation of the environmental impact results will be discussed. Then, the results (of electricity consumption and environmental impact) and discussion will be addressed in section 4.

2. State of the art review

Although injection molding is a widely studied manufacturing process in scientific literature, its main research areas have been polymer properties or production improvements; however, the variability in the energy consumption has not been analyzed in depth. Injection molding allows for the manufacture of plastic parts with complex geometries. Several phases make up the cycle of this process: the plasticizing phase when the raw material is melted, the filling of the mold, the holding of the injection pressure to assure complete filling of the part, and the cooling and ejection of the part. Some of these phases occur simultaneously. Several studies where this process is analyzed show an estimation of the energy breakdown for the injection molding process. The most intensive phases of it are the barrel heating included in the plasticizing phase, and specifically all of those phases that involve movements of the machinery, such as mold clamping or the rotation of the screw. [22]

Many authors have developed optimization methods for the process' parameters for the CAE simulation tools. For example, the method presented by Kitayama and Natsume [23], where the optimal parameters were obtained by minimizing both the volume shrinkage and the clamping force, and taking as a constraint the absence of short shots. They also noted that a lower clamping force would lead to higher productivity and lower costs per produced part, and that the use of a smaller IMM also influences the electricity consumption of the whole process. New ways of cooling systems are also evaluated in the literature in order to obtain a more efficient process by reducing the cooling time, which represents up to 80% of the molding cycle time in most of the cases. [24] To improve the quality of the product, a higher temperature of the mold is required during the filling phase but to decrease the molding cycle, this temperature has to drop significantly. There are different developing techniques called rapid mold heating and cooling methods, that try to achieve this by using electric, steam or induction heating and water cooling. [25, 26]

Some studies have also focused on the energy efficiency of the process by analyzing the electricity consumption of the process. In the research performed by Spiering et al.[18] , an energy efficiency benchmarking of the injection molding process in the automotive industry was carried out. With this study, the authors tried to gain knowledge that would allow for identifying the best practices, improvements for product designs, or predictions of the energy consumption of production plants. A structure to create an energy monitoring system (EMS) is proposed by these researchers. From measurements, they obtained a correlation of the SEC (kWh/kg) vs. material throughput (kg/h). The coefficient of determination (R^2) for this correlation was 0.7 because the process' efficiency depends on the combination of the machine, mold, part, material, etc. Nevertheless, the data presented in this paper is very general and does not indicate details about the characteristics of each measured part in which IMM was injected or the absolute values of the SEC.

Only detailed data for one part is provided. An SEC value of 1.55 kWh/kg in series production is obtained for a 3500 grams part, made out of PP with a 20% glass fiber content. This part was injected in an IMM with approximately 2000 tons of clamping force. However, data such as the cycle time of the Spiering's process, driver's technology or machine's capacity is not given.

Other authors such as Lu et al.[27] have developed algorithms to find the optimal parameters considering energy savings and quality specifications, giving this quality requirement priority over energy consumption. As these authors indicated, the relationship between energy consumption and the process's characteristics is a complex nonlinear model.

Park and Nguyen [28] presented another study on the optimization of the injection molding process, which they applied to the manufacturing of a car fender. They enumerated two possible ways to obtain energy savings. The first one was the one that would require much less cost and was the optimization of the process parameters based on a mathematical and energy model. The other alternative to obtain energy savings was the improvement of the machinery or the investment in new and more efficient technologies. Depending on the type of technology that is used to drive their movements, IMMs are commonly classified into three groups: the more conventional hydraulic machines running with hydraulic pumps at a fixed speed, hybrid machines that are machines that have the injection unit electrified, or other configurations that combine hydraulic and electric systems, and all-electric units that, as their name indicates, lack a hydraulic system.

These "all-electric" machines could achieve energy savings from 30-70% compared to other machines since the conversion of energy is more direct. [29]

Lower electricity consumption is not the only advantage of all-electric machines. They also require less maintenance since there is no hydraulic oil to replace. This also saves time in the start-up process. The motion of the clamps is faster too, allowing shorter cycles. On the other hand, high injection rates cannot be achieved by these all-electric machines, so larger parts have to be injected in hydraulic or hybrid IMMs with higher clamping forces.

An IMM manufacturer performed an experimental study with three IMMs of the same clamping force (240 ton) but different drives: one hydraulic, a hybrid and an all-electric.[30] Their SEC was measured during the production of a small part that weighted 106 grams and had a cycle time of 20 seconds. The raw material was not indicated in the study. The results showed an SEC of 0.44 kWh/kg for the hybrid, which was 1.6 times higher than the all-electric's (0.27 kWh/kg). On the other hand, the less efficient system (hydraulic) obtained an SEC of 0.65 kWh/kg, which was 2.4 times higher than the all-electric machine and 1.5 times the SEC of the hybrid machine. When increasing the cycle times, the SEC for all of the machines increases as the throughput decreases.

It is clear that there is an increasing concern about how to reach greener manufacturing processes; nevertheless, considering the reviewed state of the art and the previous work of the authors, a potential for further research in the field of the energy consumption of the injection molding process is detected. Ways to optimize through simulation models are widely discussed but there is still a lack of experimental data available in the literature. Although some benchmarks are published, not very detailed values can be derived from these studies.

On the other hand, the environmental impact related to the process is also determined as an area to be studied more deeply because there is usually a lack of data that needs to be covered to complete the Life Cycle Inventory of the manufacturing phase of a product. [18]

Through the experimental measurements performed during this research, useful information is expected to be obtained both for production engineers and LCA practitioners providing real consumption data for the injection molding process. The influence of the raw material and the relationship of the IMM with the characteristics of the injected plastic parts will be analyzed in the results section.

3. Materials and Methods

In the following section, the equipment that was used to perform the experimental energy measurements is going to be presented along with the main characteristics of the IMMs that were measured and the thermoplastic materials of the manufactured parts. Additionally, the calculation methodology to obtain the environmental impact results is going to be explained.

3.1 Measurement equipment and procedure

The equipment to perform the experimental measurements shown in Fig. 1 is the same equipment that was described in a previous study by the authors. [20] It is composed of a portable energy monitoring device (Circutor C-80) that records all of the IMM consumption and the auxiliaries connected to it. To measure the consumed power, clamps were placed to meter the current intensities of the machines in the electric panel. Three different clamps were used for these measurements (Fig. 1: c, d, e) and each of them was adequate for a range of intensities. Voltage wires were also used to measure the electricity consumption.

Fig. 1 Measurement equipment: a: Energy monitoring device, b: Voltage wires, c, d, e: Clamps, f, g: Crocodile clamps (for voltage wires), h: Security gloves

The maximum intensity must be checked before the measurements start in order to select the correct current clamp. A sampling period that covers several cycles must be selected. In addition, production must have been stable for two hours before the measurement to avoid the start-up periods. An average of three hours per test is defined to achieve enough data to ensure the validity of the measurement.

Afterwards, the energy consumption data collected by the portable device is analyzed. An average consumed energy value during the sampling period is obtained. If production was not stable during the measurement, the measurement procedure is repeated.

In addition to the recording power device, several bascules were used in order to measure the gross weight of the plastic parts. Additionally, a chronometer was used to record the cycle time. Measurements were performed in three different large factories in Madrid and Zaragoza (Spain), being the work environment the average of a factory plant with temperatures between 18-23°C.

The required consumption for the production of the plastic part will be determined as follows in (1):

$$E_{part} = \frac{t_c \ x \ E_{period}}{\tau_{sampling} \ x \ n}$$

(1)

The cycle time and the weight injected per cycle are needed to obtain the throughput (2).

$$y = \frac{w}{t_c}$$

(2)

With the obtained values from (1) and (2), the SEC (kWh/kg) can be calculated as indicated in (3).

$$SEC = \frac{E_{part} \ x \ n}{w}$$

(3)

3.2 Injection Molding Machines

A total of 12 different IMMs were measured during stable production, the operation parameters were optimized by production engineers in order to assure the quality of the manufactured parts.

Table 1 Measured Injection Molding Machines

IMM	Type of machine	Clamping force (Tons)	Maximum Injection Volume (cm^3)
A	Hybrid	8000	110000
B	Hybrid	5200	65339
C	Hybrid	3000	19300
D	Hybrid	2000	3721
E	Hybrid	1650	3721
F	Hybrid	1200	5400
G	Hybrid	1000	3721
H	Hybrid	750	4545

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I	Hybrid	400	1391
J	Hybrid	200	523
K	Hybrid	125	217
L	All-electric	85	97

Fig. 2 Measured parts

The goal was to obtain data from as wide a range of IMMs as possible. In this paper, the 12 measured IMMs have a clamping force from 85 tons to 8000 tons. The main characteristics of the machines, such as their clamping force and maximum injection volume, are included in Table 1.The maximum injection volume value included in Table 1 is used to calculate the utilization percentage of the IMMs during the production of each plastic part (4). This percentage will be considered to analyze the results in section 4.

$$\eta = \frac{\mathrm{w} \text{ x } 1000}{\rho \text{ x } \mathrm{V}_{\max}} \text{ x } 100$$

(4)

3.3. Plastic parts

Table 2 summarizes the main characteristics of the 36 parts from which the manufacturing process was measured. It indicates the raw material, the machine where the part was injected, the weight injected per cycle, the measured cycle time and the number of mold cavities. Photographs of all of the measured parts are shown in Fig. 2.

Part number	Description	Thermoplastic	IMM	w (g)	t_c (s)	n
1	Container (2400l)	HDPE	A	71800	216.00	1
2	Container (1000l)	HDPE	B	30300	147.00	1
3	Container Lid (3200l)	HDPE	C	10500	175.00	1
4	Container Lid (2200l)	HDPE	C	8700	194.00	1
5	Encasement #1	PP	C	7258	140.20	1
6	Car Bumper	PP+EDPM+PE+10T	C	4695	118.00	1
7	Car Front part #1	PP+EDPM+10T	C	3773	106.00	1
8	Car Interior Part #1	PP+EDPM+15T	C	1802	77.60	1
9	Car Front part #2	PP+EDPM+20T	C	1589	91.00	1
10	Weatherproof Luminaire Diffuser (Alhama 2x58)	PC	D	646	22.00	1
11	Weatherproof Luminaire Housing (Aragón 2x36)	PC	E	745	33.70	1
12	Paper bin	HDPE	F	2778	139.00	1
13	Car Interior Part #2	PP	F	1560	70.00	2
14	Paper Container Part	HDPE	F	1253	81.00	1
15	Weatherproof Luminaire Diffuser (PE 2x36)	PC	G	495	24.40	1
16	Weatherproof Luminaire Diffuser (PE 2x36)	PMMA	G	489	29.05	1
17	Weatherproof Luminaire Diffuser (PE 1x36)	SAN	G	383	24.55	1
18	Encasement #2	PP	H	3407	100.00	1
19	Paper Container Small Part	HDPE	H	836	40.00	1
20	Container Part	HDPE	H	1336	162.00	1
21	Ring	HDPE	H	260	42.90	1
22	Container Pusher	POM	I	310.75	37.60	2
23	Car Bumper Lid	PP	I	288	84.00	2
24	PA Filled Part #1	PA+50% LF	I	128.58	48.00	2
25	Container Lock Bar	PA	I	161.24	29.20	1
26	Shock Absorber Housing	HDPE	I	154.12	47.68	2
27	Ring 2 (350 mm)	HDPE	I	106.00	40.30	1
28	Container Axis Part	HDPE	I	100.50	44.40	8
29	Weatherproof Luminaire Lid	ABS	J	39.58	22.00	1
30	Weatherproof Luminaire Snap-fits (3 pieces)	PA	K	67.66	14.00	4
31	PA filled Part #2	PA+30% GF	L	68.00	37.20	2
32	Container Axis Part	PP (100% recycled)	L	100.48	45.00	8
33	Container Red Ball	ABS	L	37.00	53.00	2
34	PA Part	PA	L	16.08	11.80	2

35	Container Snap-fit	PP	L	14.36	12.50	4
36	Container Snap-fit	HDPE	L	15.00	15.00	4

3.4. Environmental Impact Assessment Methodology

To calculate the environmental impact of processing these plastics parts, an adaptation of the methodology described in our previous research is going to be applied. [20] In the previous article, an analysis on how the EcoInvent v3 Life Cycle Inventory database characterizes this process was conducted. To assess the environmental impact of the HDPE plastic parts, a customized dataset was prepared: removing elements not directly related with the injection molding process, considering data values of a more conventional thermoplastic (PP) instead of the EcoInvent's average obtained from values of PVCs, PPs and PETs processing factories, and replacing the average electricity consumption value with the SEC of each part. The European electric mix was selected in order to allow for a comparison to the original EcoInvent dataset. [20] The electricity consumption of the process was proven to be, in this previous study, the most important factor in the environmental impact results. It was also shown how the electricity consumption can differ greatly from the EcoInvent dataset's SEC value (1.47 kWh/kg). [31]

For this study, the Spanish electric mix is going to be used instead of the European because all of the plastic parts were manufactured in Spain. In addition, for the plastic parts that were injected in the all-electric machine, the environmental impact of the lubricating oil of the machine will not be taken into account. Therefore, the functional unit that will be assessed to calculate the environmental impact of the processing of 1 kg of injected plastic will contain the values derived from the EcoInvent methodology summarized in Table 3.

Table 3 Dataset for the environmental impact calculation

Description	EcoInvent v3 dataset	Value
Lubricants for hydraulic circuits	Lubricating oil {GLO}| market for | Alloc Def, U	1.67E-05 kg
Water	Water, cooling, unspecified natural origin	1.11E-02 m^3
Electricity	Electricity, medium voltage {ES}| market for | Alloc Def, U	Measured SEC (kWh/kg)
Plastic waste	Waste plastic, mixture {GLO}| market for | Alloc Def, U	0.005 kg
Infrastructure	Packaging box factory {GLO}| mar ket for | Alloc Def, U	1.43E-09 p

To calculate the environmental impact of this dataset, the software SimaPro 8 has been used. [32] The results are reported in mPt of the ReCiPe- Endpoint indicator. This methodology is recommended in the literature when only one value is required [33], which will facilitate engineers to choose between different IMM options.

4. Results and Discussion

4.1 Energy measurement results and discussion

In this section, the results of the experimental measurements are going to be presented and analyzed.

Different representations are going to be displayed in order to analyze and draw conclusions from the performed measurements. First, the relationship between the SEC and the kg/h injected per part or the utilization of the capacity of the machine will be discussed, analyzing and sorting the data by the IMM and by the material. Additionally, the results of the measurements where the same geometry was injected in different machines or with different raw materials will be analyzed.

The total required electricity to manufacture each plastic part was calculated, as explained in section 3.1. The results are shown in Table 4.

Table 4 shows that, generally, the heavier a plastic part is the more kWh are consumed to manufacture it. However, the real phenomenon is much more complex because several factors play an important role in energy consumption, such as the cycle time, IMM or material properties. An example of this can be seen with part #8, which has lower energy consumption and more weight than part #9. From Table 2, it can be observed that cycle time is higher for part #9, which justifies the higher energy consumption. From now on, in order to properly analyze the measurements, and establish comparisons between the case studies, the results will be presented based on the functional unit (1 kg of injected plastic part) using the SEC value. Fig. 3 shows the calculated SEC values for each analyzed part.

The average value for the measurements is 1.056 kWh/kg, which is 28.2% lower than EcoInvent's SEC value (1.47 kWh/kg). It can also be seen that the variability in the results is high. The standard deviation of this sample is 0.543 kWh/kg and its coefficient of variation ($CoV= \sigma/\bar{X}$) is 51.4%. The maximum SEC value is observed for part #9 injected in machine C (2.563 kWh/kg) and the minimum is for part #31 injected in machine L (0.375 kWh/kg). It is important to notice that the all-electric machine (L, #31- #36) registers the lowest average consumption per kilogram (0.529 kWh/kg).

Analyzing the distribution of the measurements, the majority of the SEC values (22 of 36) are approximately in the range between 0.4-1.2 kWh/kg. The analyzed samples do not exhibit a direct relationship between the size of the machine/part and the SEC, as can be observed with the heavier parts injected in the IMMs: “A”, “B”, and “C”. This indicates that the electricity consumption is not directly related to the machine's size but to the relationship between the IMM and the injected part. On the other hand, only the all-electric machine (L), achieves consumptions lower than 0.4 kWh/kg in these case studies.

The IMM type is not the only influence on the SEC. Fig. 4 shows the SEC of all of the measurements against the throughput of every part by sorting the data by the machine's clamping force. This graph

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shows that for the same throughput value, not only can the SEC differ significantly, but the injection molding process also has a very wide throughput range with a maximum value for the measured parts up to 1200 kg/h and a minimum value of 2.5 kg/h.

Table 4 Total Energy Consumption for the manufacture of the plastic parts

Part number	Weight injected per cycle (g)	kWh/part	Part number	Weight injected per cycle (g)	kWh/part
#1	71800	30.949	**#19**	836	0.593
#2	30300	23.870	**#20**	1336	1.805
#3	10500	9.273	**#21**	260	0.598
#4	8700	9.287	**#22**	310.75	0.087
#5	7258	7.232	**#23**	288	0.184
#6	4695	5.698	**#24**	128.58	0.124
#7	3773	4.553	**#25**	161.24	0.192
#8	1802	2.912	**#26**	154.12	0.126
#9	1589	4.072	**#27**	106.00	0.189
#10	646	0.567	**#28**	100.50	0.023
#11	745	0.866	**#29**	39.58	0.048
#12	2778	1.442	**#30**	67.66	0.011
#13	1560	0.375	**#31**	68.00	0.013
#14	1253	1.128	**#32**	100.48	0.005
#15	495	0.539	**#33**	37.00	0.013
#16	489	0.493	**#34**	16.08	0.005
#17	383	0.359	**#35**	14.36	0.002
#18	3407	2.204	**#36**	15.00	0.002

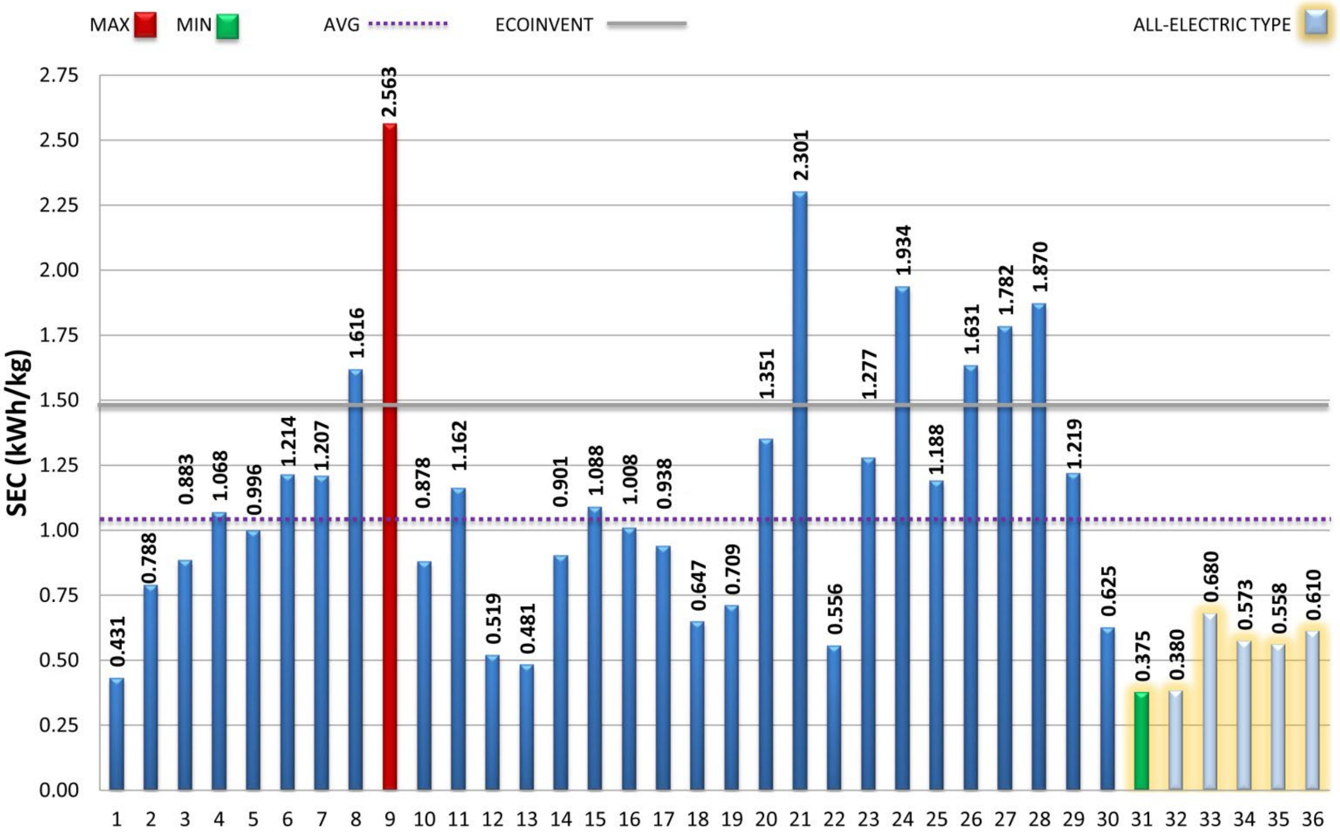

Fig. 3 SEC of all of the measurements

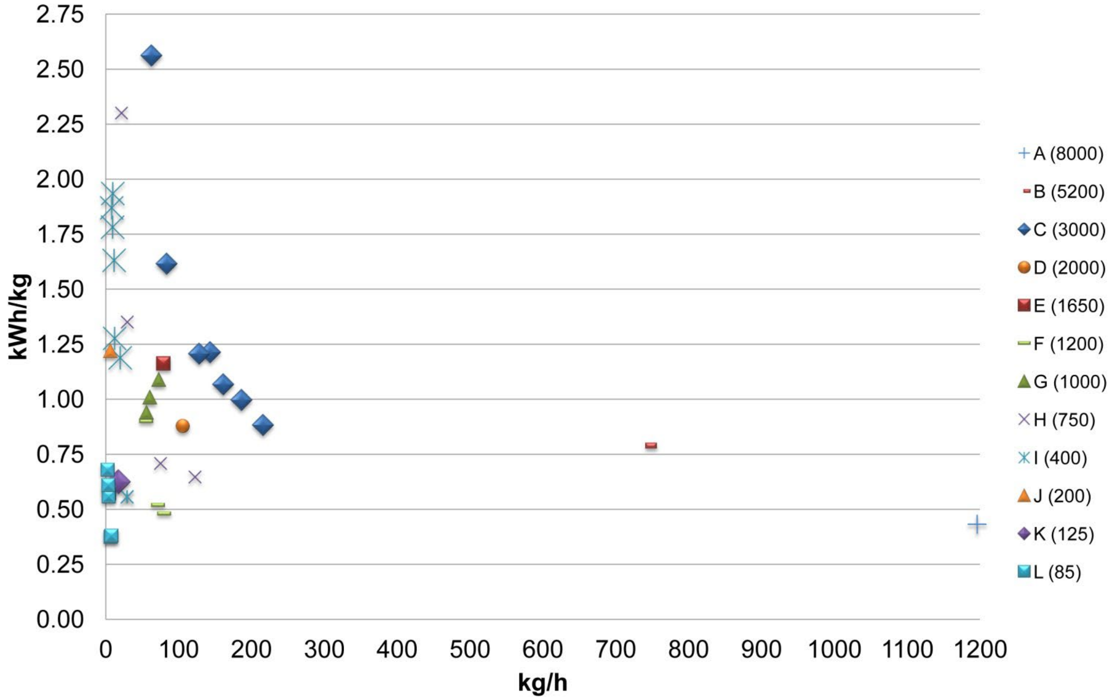

Fig. 4 SEC vs. throughput (sorting by IMM)

A descending tendency for the consumption is observed in Fig. 4 as the throughput increases, as shown in the studies mentioned in the state of the art review. Moreover, differences between the IMMs are also relevant. By isolating the results from the IMMs with at least four measurements (IMMs: C, H, I and L), Fig. 5 shows how potential functions for each IMM can be correlated with the experimental data with high R^2 values (> 0.875). The more clamping force the IMM has, the more displaced the curve is to the right zone of the graph. That is, in general, for the same throughput value, the SEC will be higher for the IMM that has a higher clamping force.

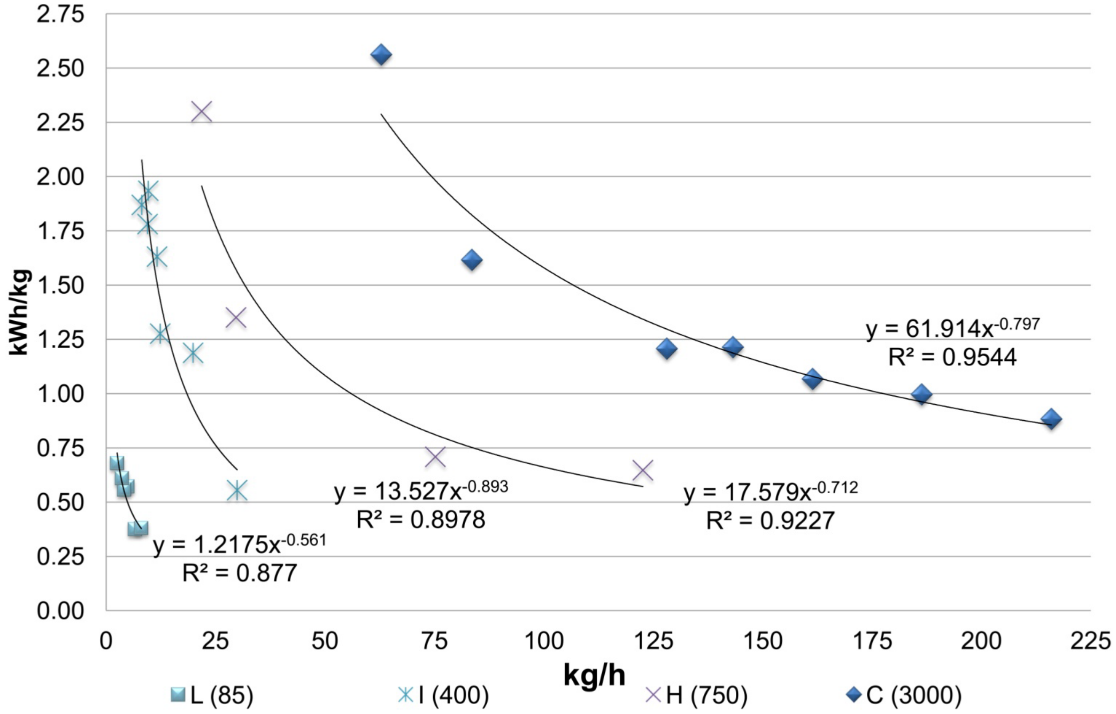

Fig. 5 Potential correlations: SEC vs. throughput (sorting by IMM)

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This tendency is characterized by the correlation value (R^2), which makes physical sense because the constant process' consumption necessary to keep the machine functioning during idle times, is divided by more kilograms per hour. Linear regression analysis (LRA) has been a useful method to identify the best practices and establish benchmarking baselines. [34]

To further analyze these tendencies, the relationship between the utilization percentage of the IMM and the SEC of the process is calculated by (4). It is expected that as the utilization of the IMM is near its full capacity, obtaining higher throughputs, its electricity consumption would be divided by the maximum possible plastic weight; therefore, the choice of machine size will be optimized for that part. Using (4), the relationship between the use of the IMMs capacity and the electricity consumption of the process can be analyzed (Fig. 6).

As with the throughput, a descending tendency of the electricity consumption is observed; however, unlike with the throughput, with this percentage, differences caused by the IMMs sizes are not shown because this is a dimensionless parameter. With this approach, comparisons between the IMMs can be made by taking into account their used capacity. Generally, the higher the percentage of the machine's capacity that is used, the less kWh per kg is required for the injection molding process. However, smaller differences can be observed for the "L" machine (85 tons, all-electric), which maintains low SEC values regardless of the percentage of utilization of the IMM. The all-electrical configuration explains this result.

To analyze the influence of the material, the relationship between the percentage of utilization of the IMM and the SEC are shown in Fig. 7 for all of the materials. These results show that the studied PP filled parts registered the highest SEC values, as was reflected in the study by Spiering et al.[18], but it also has to be taken into account that the machines used to manufacture them have low utilization percentages. The unfilled PPs parts, which have lower SEC values, even with low percentages of utilization, are all injected in the "L" machine (85 tons, all-electric).

Because Fig. 7 does not show any clearly defined tendencies, to continue identifying the influence of the raw material in the electricity consumption of the process, the results of the IMMs with four measurements or more (IMMs: C, H, I and L), shown in Fig. 5, have been sorted by material, namely, HDPE, PP, PP filled, POM, PA, PA filled and ABS (Fig. 8).

In Fig.8, it can be observed that the majority of the measurements follow the descending tendency of SEC vs. throughput, as can be clearly seen for machines "C" and "H". For the "I" machine (400 tons) there are measurements that deviated slightly more from this mentioned tendency. For example, the one that corresponds to part #24, made out of filled PA with a very high percentage (50%) of long glass fiber, which has a slightly higher SEC than the tendency would indicate. This can be caused by the use of glass fiber fillers that generate an increase in the melt viscosity. [35] Moreover, the PA itself is an amorphous thermoplastic, which means that the macromolecular chains of the amorphous thermoplastics are entangled with no particular order and since the melt's viscosity depends on this structure, this raw material has a high viscosity that increases the SEC.[36]

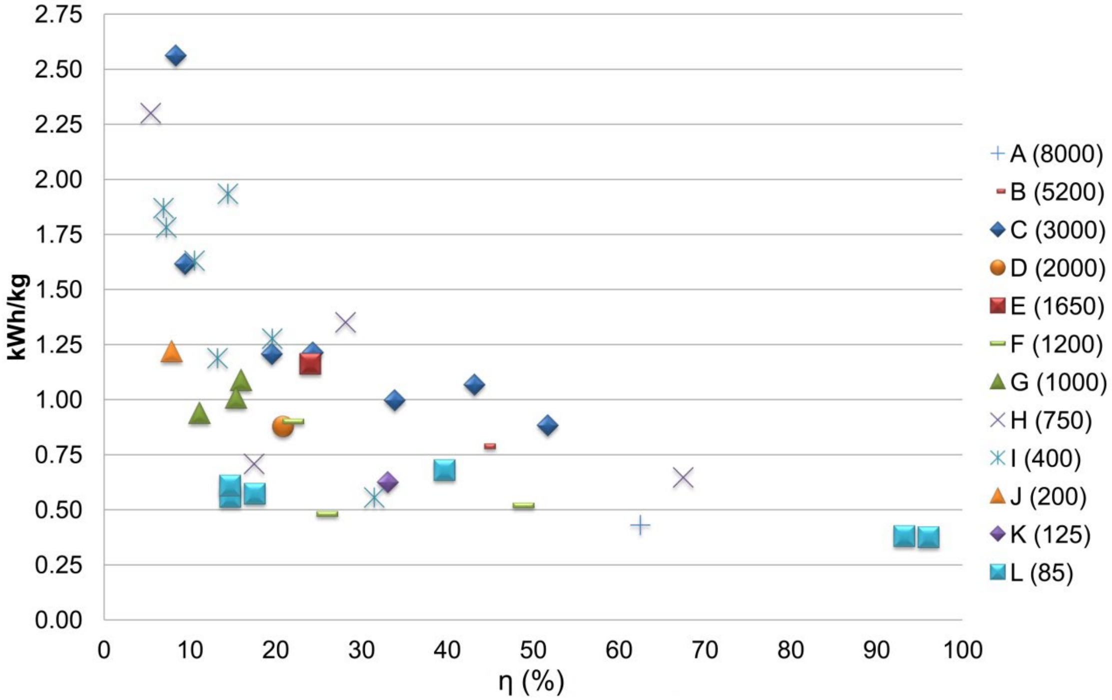

Fig. 6 SEC vs. η (sorting by IMM)

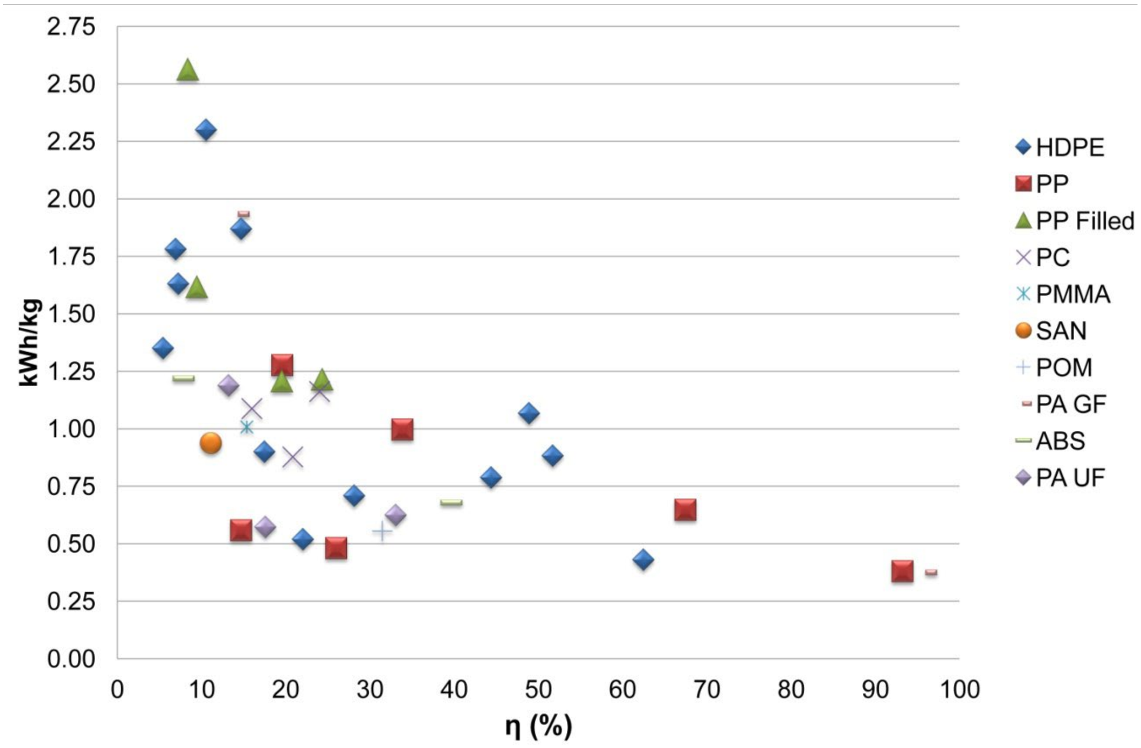

Fig. 7 SEC vs. η (sorting by raw material)

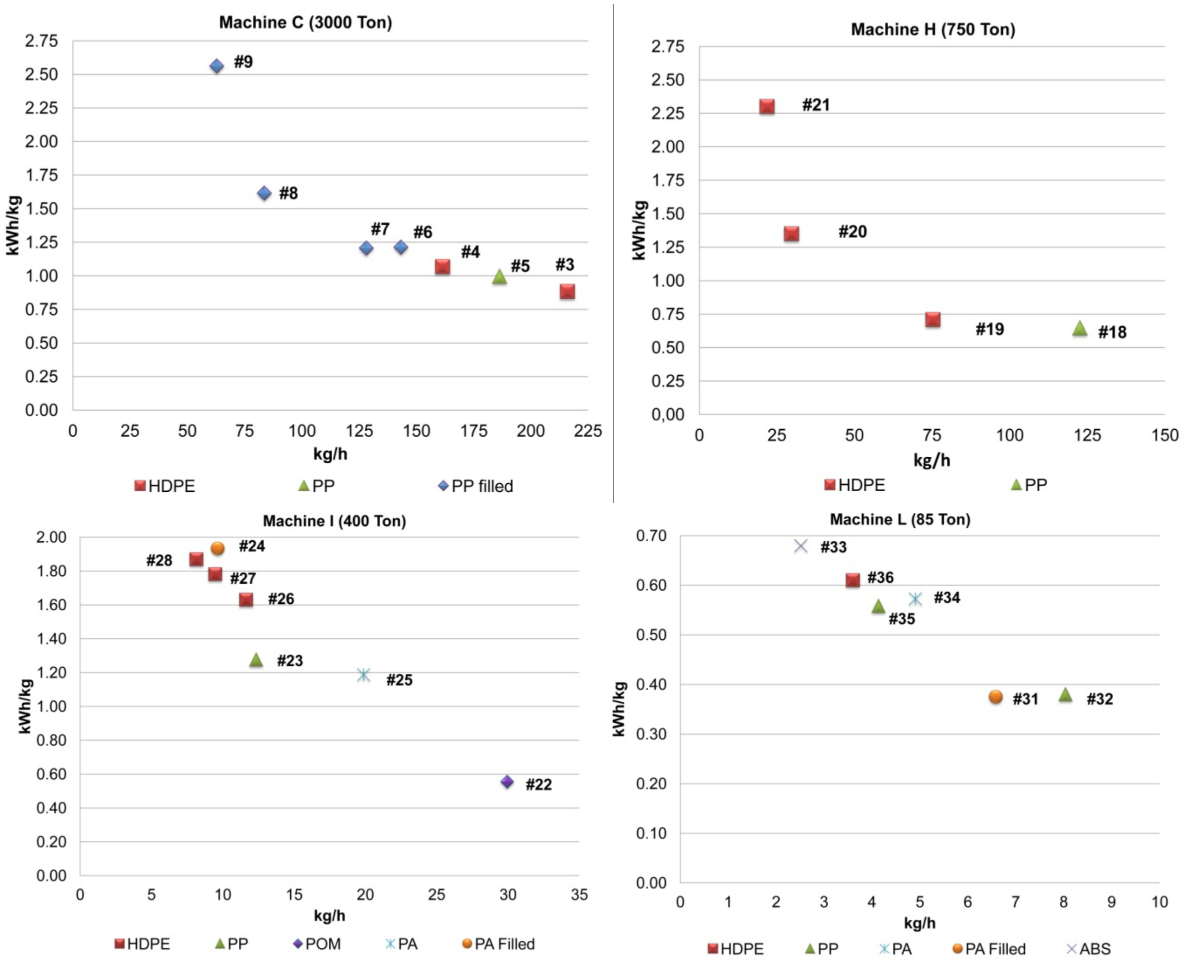

Fig. 8 SEC vs. kg/h (IMMs C, H, I, and L) sorted by raw material

There are also some interesting combinations to analyze in the measurements, which focuses on the part's characteristics. For example, parts #35 and #36, shown in Fig. 8, have the same geometry and they are injected in the same IMM ("L"). However, their raw material is different. In this case, the manufacturing process of the #36 HDPE part registers a higher SEC than the PP part (#35) (+9.3%). This result may be due to slight differences in the specific heat of these two thermoplastics, which causes the required energy for the plasticizing phase in the HDPE part to be higher. This stage is one of the most intensive phases of the process in terms of energy. The required energy to heat the barrel during the plasticizing phase could be estimated as indicated in (5).[37]

$$E_{plast} = \frac{s_h \ \text{x} \ \Delta T}{3600}$$

(5)

Although the barrel has insulation, due to possible losses to the surroundings, a coefficient to include the possible yield of the system would have to be considered, but because the purpose of this analysis is to obtain a first estimation and in this case the losses are machine dependent, the value of this yield coefficient would be considered to be 1.

Another explanation for the obtained differences can be found in the requirements for the cooling phase since the recommended ejection temperature for the PP is 70°C whereas the temperature is 50°C in the HDPE part; therefore, the cooling time requirement for the PP part is lower and the total cycle time will be lower for the #35 PP part, as shown in Table 2.

Parts #28 and #32 also have the same geometry, but they are injected in different IMMs, the raw material is different (HDPE and PP, respectively) and the IMM is different. A high utilization of the capacity of the machine combined with the use of a more efficient technology (all-electric) allows for obtaining one of the lowest SEC values for part #32 (0.38 kWh/kg). The low utilization of the "I" hybrid machine for part #28 manufacturing leads to a much less energy efficient process.

As previously discussed for part #24 in the explanation of Fig. 8, from samples #15 and #16, the role of the raw material's viscosity can also be analyzed. For these samples, the IMM and the part geometry remain the same, but the injected thermoplastic is different (PMMA vs. PC). The results show that the electricity consumption of the injection molding process is 7.96% higher for the polycarbonate part than the PMMA part. The viscosity of polycarbonate is higher than the viscosity of PMMA for the high shear rate values (over 10^3 1/s) used in the injection molding process [38], therefore, the phase of filling the mold and holding would be more energy intensive. On the other hand, the part's geometry (see Fig. 2) has a long flow length and a low thickness (1.5 mm). To reduce the effect of the frozen layer that decreases the effective area for the polymer to flow, which increases the required injection pressure, it is necessary to heat the mold up to temperatures of 100°C in the case of polycarbonate and up to 70°C in the case of PMMA [39]. This fact has a direct influence on the total electric consumption for the process for each part.

As previously stated, along with the movements of the machine, the barrel heating of the plasticizing phase is one of the most intensive phases of the process in terms of energy. To further analyze the results, by applying (5) to the measurements we can estimate the percentages that this phase has over the total results.

In Fig. 9, different tendencies can be observed for each IMM (the ones that have four or more measurements).

With this estimation, the barrel heating percentage presents values between 4 and 28% of the total SEC, being this percentage smaller as the size of the machine increases (4-12% for "C"). For higher throughputs, the importance of the plasticizing phase increases as the idle times decrease; therefore, the losses, as the capacity of the IMM is better adjusted.

Additionally, it is remarkable that for the two smaller IMMs and overall, for the all-electric machine, this percentage is higher (12-28%) as the power required for the movements is lower given the lower clamping forces and the movements system efficiency.

4.2 Environmental impact results and discussion

The environmental impact of the 36 processes has been calculated using the ReCiPe Endpoint indicator and following the methodology explained in subsection 3.4 "Environmental impact assessment methodology".

The overall impact of the manufacturing of the part can be obtained by assessing the dataset of our functional unit (see section 3.4) taking into consideration its SEC and its gross weight. The results are shown in Table 5.

As can be seen, the results in Table 5 are mostly proportional to the results in Table 4 because the electricity consumption is the most dominant factor in these environmental impact results [19, 20]. That is, a reduction in the SEC implies almost the same reduction in the environmental impact of the process. To allow comparisons between parts, as previously shown in subsection 4.1 with the electricity consumption measurements, the results are going to be displayed per kilogram of injected plastic, which is the functional unit of the study (Fig. 10).

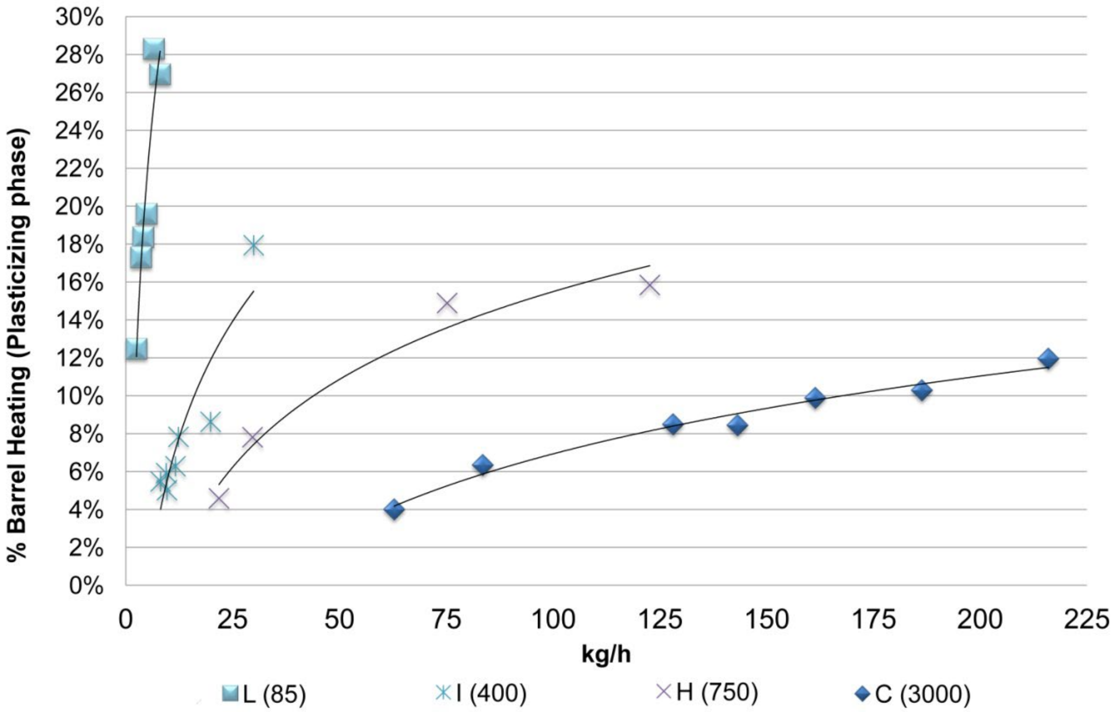

Fig. 9 Percentage of plasticizing phase over the electricity consumption vs. kg/h

Table 5 Total Environmental impact of the manufacture of the plastic parts (mPt ReCiPe)

Part number	Weight injected per cycle (g)	mPt ReCiPe/part	Part number	Weight injected per cycle (g)	mPt ReCiPe /part
#1	71800	1469.102	#19	836	27.222
#2	30300	1090.878	#20	1336	80.871
#3	10500	421.654	#21	260	26.497
#4	8700	419.242	#22	310.75	4.048
#5	7258	327.295	#23	288	8.252
#6	4695	256.149	#24	128.58	5.526
#7	3773	204.712	#25	161.24	8.618
#8	1802	129.897	#26	154.12	5.606
#9	1589	180.070	#27	106.00	8.406
#10	646	25.797	#28	100.50	1.045
#11	745	38.961	#29	39.58	2.168
#12	2778	67.510	#30	67.66	0.489
#13	1560	17.654	#31	68.00	0.613
#14	1253	51.264	#32	100.48	0.229
#15	495	24.295	#33	37.00	0.579
#16	489	22.292	#34	16.08	0.214
#17	383	16.300	#35	14.36	0.093
#18	3407	101.745	#36	15.00	0.106

The injection molding processes of parts #9 and #31, which are the ones that achieved the highest and lowest values of SEC, are also the ones that have the highest and lowest environmental impact results per kilogram (113.32 vs. 18.03 mPt ReCiPe/kg).

The average environmental impact of the injection of a plastic part with our methodology [20] is 47.7 mPt/kg. Due to the variability of

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the SEC results, the environmental impact variability is also high (σ= 23.65 mPt ReCiPe/kg, CoV= 49.6%). The average value is 56.7% lower than for the EcoInvent's dataset (111.01 mPt/kg ReCipe), which uses the European electric mix instead of the Spanish electric mix and has broader system limits as previously explained in the methodology section.

The environmental impact results for the all-electric machine (#31- #36) are the lowest with an average of 24.7 mPt ReCiPe/kg. This aspect again shows the high influence that electricity has on the environmental impact.

As also occurred with the electricity consumption, the low range of the environmental impact distribution (0-20 mPt/kg) is only obtained for the processes carried out in the all-electric machine .

However, results lower than average, such as the ones in the range between 20 and 40 mPt/kg, are not only achieved in the all-electric machine but also in hybrid machines. As with the electricity consumption, the majority of the measurements (25 of 36) are in the medium range of the distribution within 20-60 mPt/kg.

On the other hand, the processes with higher impact (> 80 mPt/kg) are the ones with higher SECs regardless of the size of the used IMM. The already observed descending tendency of the electricity consumption with the throughput is also maintained with the environmental impact, as Fig. 11 shows. Analogously, the environmental impact can differ a lot for the same throughput value, making again the differences between the IMMs relevant.

Due to the direct relationship between the electricity consumption and environmental impact, a high utilization of the machine's capacity also implies a low environmental impact from the injection molding of the plastic parts (Fig. 12). The same conclusions as with the electricity consumption can be drawn by analyzing each part for the environmental impact results. For parts #35 and #36, which were injected in the same IMM and have the same geometry, the different raw material makes the environmental impact of the processing of the latter (HDPE part) 8.7% higher. The same occurs with parts #15 and #16, where the processing of the PC registers an environmental impact that is 7.7% higher than for the PMMA's part.

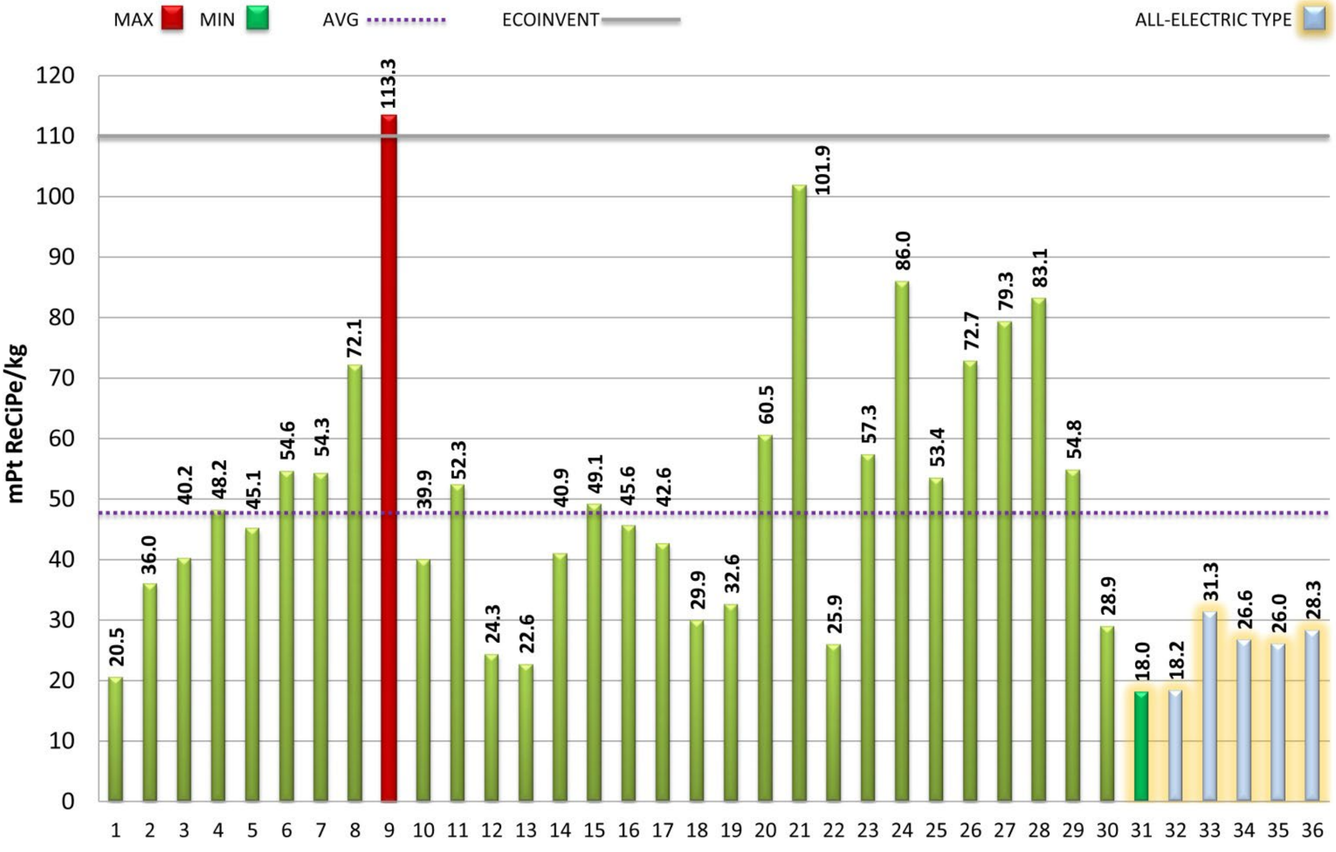

Fig. 10 Environmental impact of the injection of 1 kg of each plastic part

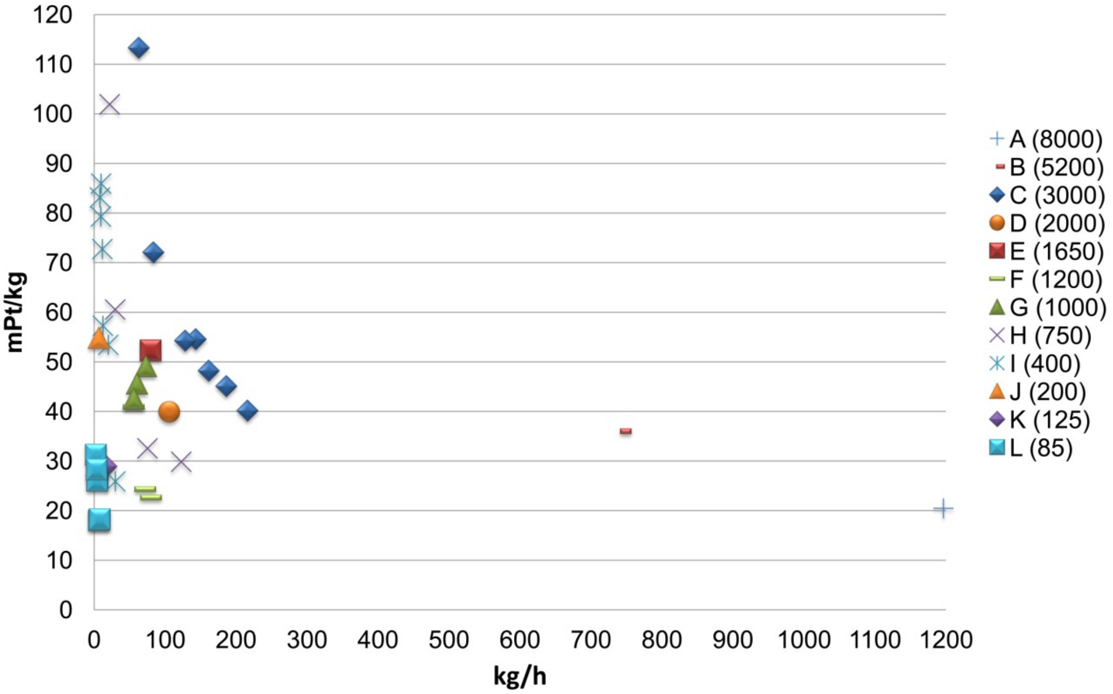

Fig. 11 Environmental impact (mPt ReCiPe/kg) vs. throughput (sorting by IMM)

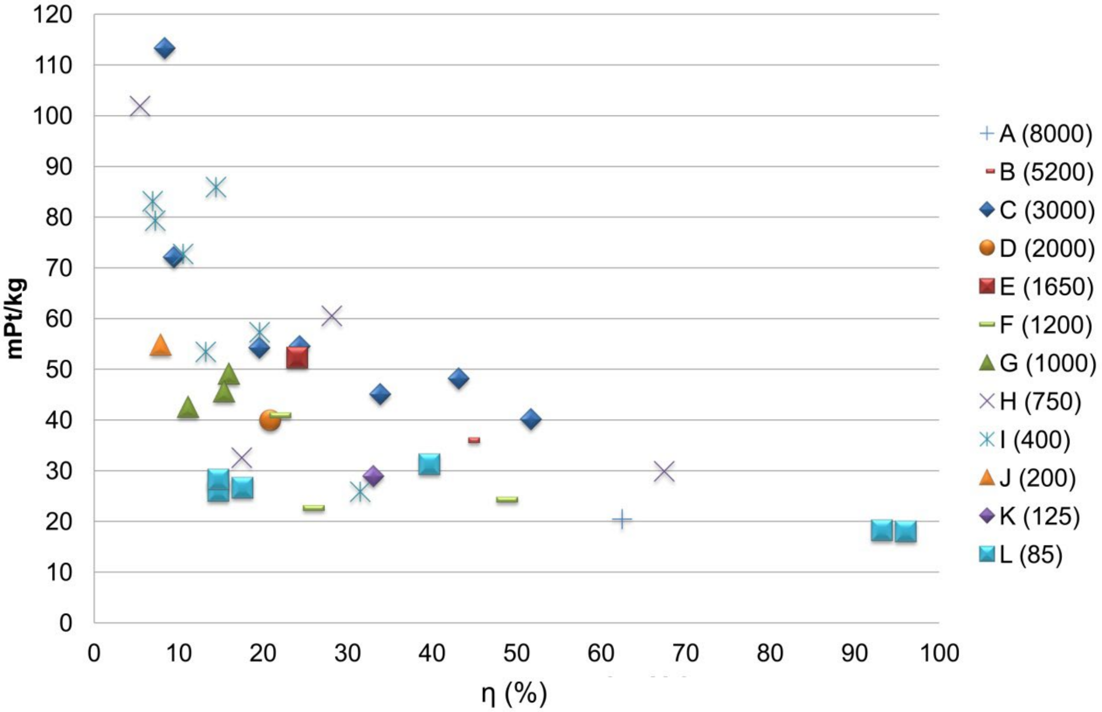

Fig. 12 Environmental impact (mPt ReCiPe/kg) vs. η (sorting by IMM)

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5. Conclusions

The importance of deeply analyzing the energy efficiency of the manufacturing process has been discussed in this study. Better knowledge is required in order to identify potential improvements that allow for reducing the electricity consumption along with the related cost and the environmental impact of manufacturing companies.

The electricity consumption of several IMMs has been analyzed by monitoring the electricity consumption of 36 different case studies. The obtained results have shown how the type of machine influences the electricity consumption. As indicated by Knights [29], who indicated a possible range of 30-70% in energy savings, it is quite remarkable the savings that were achieved by the studied all-electric machine (54.4%) in comparison with the other equipment for our measurements (0.529 kWh/kg of average SEC for the all-electric machine versus 1.161 kWh/kg for the rest of the IMMs). The average SEC for all the case studies is 1.06 kWh/kg, which is 27.8% lower than the statistic value used by the EcoInvent database. These SEC measurements have high variability (CoV: 51.4%), and the maximum and minimum consumption values were achieved by processing parts #9 and #31 (2.563 and 0.375 kWh/kg, respectively). Part #9 was injected into a 3000 ton hybrid IMM and it used less than the 9% of its total capacity. On the other hand, part #31 was manufactured in an 85 ton all-electric IMM at almost its full capacity.

The importance of the high utilization of the IMM's capacity has also been highlighted. With high percentages of utilization, the SEC of the injection molding process is minimized. Together with the machine's movements, the plasticizing phase is one of the most energy intensive phases. It has been observed how the percentage of the total SEC that this phase uses rises as the throughput increases. Additionally, its influence is higher for smaller machines because the energy demand of the machine's drivers is lower; therefore, the energy consumption percentage caused by the barrel heating is higher, so actions to reduce the heating losses would be more effective in these cases.

These electricity consumption measurements have been used to characterize the environmental impact of the manufacturing of the analyzed parts given the high influence that the electricity consumption has on this process. An average of 47.7 mPt ReCiPe/kg is obtained for all of the case studies (57% lower than EcoInvent's database value) with parts #9 and #31 being the parts with the maximum and minimum values (113.32 and 18.03 mPt ReCiPe/kg).

Although there is also a high variability in the results, the clear correlation between a high utilization of the IMM and the low environmental impact of the process is kept as it happens with the electricity consumption.

Although the lack of data present in some of the studies mentioned in the state of the art review makes it difficult, and in some cases impossible, to make comparisons, the results from this work can be compared to some of them, revealing similarities and differences. For example, the most similar parts in weight in our study compared to the measurements performed by Lechner [30] are parts #27, #28 and #32, which have higher SEC values in our study (1.78, 1.86 and 0.38 kWh/kg, respectively). The differences are caused by higher cycle times (more than double) and therefore lower throughputs and used capacity. Regardless the increase in productivity the importance of reducing the cycle time by optimizing the process's parameters or via design, e.g., reducing the parts thickness, are very relevant.

On the other hand, the measurements presented by Spiering et al. [18] do not allow for individual comparisons because they are all gathered in one graph without indicating the values. The correlation value of all of their measurements is 0.7 (including several IMMs and materials). Most of our analyses have been carried out by clustering measurements, which resulted in correlation values greater than 0.875.

Part #7 in our study has similar characteristics to the one presented by Spiering et al. [18], mentioned in the state of the art review. Part #7 has an SEC of 1.2 kWh/kg (22.6% lower than Spiering's), which could point out that either the throughput is higher for our case or the machine's capacity or technology is more optimized. Additionally, the quantity and type of filler (talc versus glass fiber) could have some influence. The knowledge that these kind of measurements gives to the companies could be used not only to assess their environmental footprint but also for energy and cost reduction purposes by using these measurements as an internal benchmark. The variability observed in the previous research from the authors is again present incorporating measurements with more different raw materials and IMMs, this variability should be taken into account by LCA practitioners while analyzing the injected plastic parts. Engineers should consider actions such as reducing the cycle time of the process without risking the product's quality or the use of a more adjusted machine according to the part's dimensions to achieve lower SEC values. Another factor to take into account is that materials with high viscosity or filled tend to register higher energy consumption values making this aspect especially relevant for parts with low thicknesses.

Additionally, manufacturers are encouraged to invest in all-electric machines instead of in hydraulic or hybrid machinery because their performance would always be more efficient. Although in the past these machines were limited in their characteristics, technology has been evolving, and electric IMMs of up to 3500 tons of clamping force are available in the market making them big enough to manufacture most plastic parts. [40]

There is further research potential that should be carried out to overcome the limitations of this study. Other injection technologies such as Mucell or gas injection could be analyzed by following the procedure used in this paper. If possible, the measurement of the electricity consumption of each IMM subsystem could contribute to further comprehending the relationships between the part, IMM, parameters and total electricity consumption. More measurements of the same mold with different raw materials or injected in different IMMs could be performed to further independently analyze the influence of these parameters.

It could also be interesting to expand the number of analyzed materials, measuring plastic parts made of PVC, or other common thermoplastics such as PET, that are not covered in this study. Moreover, how the percentage of filler, such as glass fiber, influences the electricity consumption of the same part could contribute to the knowledge of this topic.

All these research lines could enable the design of plastic parts and their molds in the future by taking into account factors such as the available IMMs and considering the design actions such as the definition of thickness, flow length, number of gates or cooling to develop the most efficient combination considering the process and industry constraints.

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