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Definition and evaluation of good manufacturing practices for plastic injection molding

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Abstract In this work, the impact of good manufacturing practices (GMP) on the specific energy consumption (SEC) of plastic injection molding process, in 9 representative companies in Colombia, was studied. The GMP applied to the injection molding process and the degree to which they are adopted by the companies were defined. Afterwards, the SEC of 17 representative injection molding processes in those companies were evaluated. Finally, the impact of applying the GMP and their effect on SEC were studied. The degree of application of GMP on the analyzed companies ranges from 35 to 72%. A single SEC value could not be established for all the injection systems, because it depends on the injected weight and the productivity of each mold-machine-material combination. Nevertheless, a characteristic curve was defined for different systems. A relationship between the application of GMP and SEC was found. It was observed that all GMP contributed to improve the SEC, with different significance, ranging the relevance from 6 to 14%. Finally, it was concluded, taking in consideration a representative company, that "Plasticizing" and "Drive Units" were the most relevant categories to impact the SEC.

Keywords Good manufacturing practices · Plastics processing · Specific energy consumption · SEC · GMP

Introduction

There is a relationship between quality, competitiveness, and productivity (Kafetzopoulos et al. 2015). Quality is understood as meeting the customer requirements; competitiveness is defined as delivering services and products with higher added value than the competition; and productivity is defined as producing with the optimal quantity of resources (Claver et al. 2001; Samson and Terziovski 1999; Vanichchinchai and Igel 2009). Therefore, these are three very important factors in any manufacturing process, including polymer injection molding; however, often times, they are contradictory as well (Singh and Verma 2017).

There are several approaches to improve the synergy between quality, competitiveness, and productivity (Palange and Dhatrak 2021; Schlüter and Rosano 2016), including good manufacturing practices (GMP) (McCormick 2002). Under the GMP methodology, there are two different concepts: The first one

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seeks to improve manufacturing processes in terms of human safety and health, to produce satisfactory products in specific markets, such as the food or pharmaceutical sectors. The second one is the intervention of the processes, to achieve quality products by optimizing the resources used for manufacturing, which ensures the competitiveness of the company (Meekers et al. 2018; Park and Nguyen 2014).

On the other hand, specific energy consumption (SEC) is an indicator used to measure manufacturing performance (Spiering et al. 2015). The SEC shows the result of correct processes operation; for that reason, it is an excellent tool, applicable to any region in the world, to measure the overall manufacturing plants performance (Deng et al. 2017; Kluczek and Olszewski 2017; Zhao et al. 2017). A recent work underlines the need to understand the SEC of polymer processing, studying the internal and external factors that affect the process (Abeykoon et al. 2021; Matarrese et al. 2017). Therefore, they suggest that SEC is affected by inefficiencies related to production planning, nonconforming products, process, machinery, and outdated devices (Estrada et al. 2018; Macedo et al. 2019; Rashid et al. 2020).

Also, the SEC is used as an external benchmarking to compare different sites and injection molding machinery performance. The external benchmarking of a particular site is established by calculating the energy consumption of an injection molding facility over a period of time, normalized by the total production in kilograms, the period of time in hours, and the number of operating machines. The external benchmarking of a machine is established by calculating the power needed by a specific injection molding machine normalized by the production volume in kilograms per hour. Production volumes are calculated with the part weight and the cycle time (Spiering et al. 2015). The SEC is correlated with the production volume (Iwko and Steller 2018; Thiriez and Gutowski 2006). The most complete and well-documented study of external benchmarking of injection molding machines was published by Kent (D. R. Kent 2008a; R. Kent 2008b). It is important to remark that the study by Kent was conducted on hydraulic machinery (nor hybrid and all-electric were considered) and the influence of materials, parts, machine, and mold coupling was ignored. Some European standards have been developed to help users to classify injection molding machinery by energy efficiency (Euromap 2013a) and determine the energy consumption of injection molding machines (Euromap 2013b).

This study aims to determine the GMP in injection molding processing that affects the SEC, in a particular Colombian region.

Methods

Determination of GMP and development of the diagnostic tool

The GMP for plastic injection processes, presented in this work, are 118 strategies based on the state of the art of technology and processes. Such strategies are framed on 11 categories related to the Plan-Do-Check-Act cycle (PDCA) shown in Fig. 1. The SEC is considered as an output variable, and it is defined as the ratio between the energy consumed by the injection molding machine (kWh) and the kilograms of compliant products (kg).

Related to the PDCA cycle, the "Plan" includes all categories related to the processes before the polymer is injected. Therefore, it includes the "Storage and resin handle," "Production planning," "Occupational health and safety plans," "Customer management," and "Maintenance plans." The "Do" includes the actions and processes related to the injection of

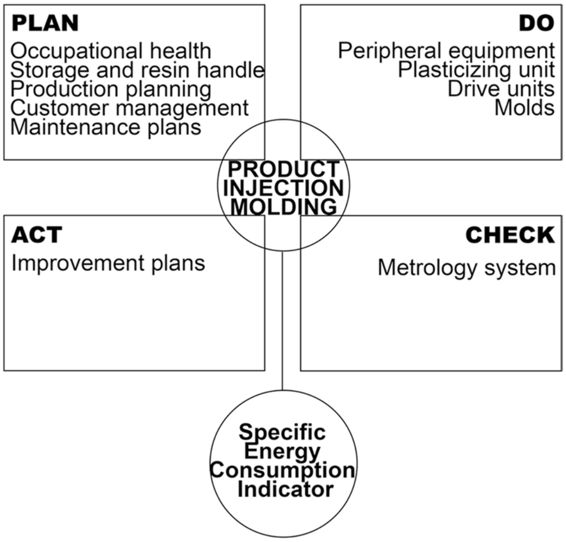

Fig. 1 Plan-Do-Check-Act cycle for the diagnostic GMP tool development

plastic in the mold, such as the control of “Peripheral equipment,” “Plasticizing units,” “Drive units,” and “Molds.” The “Check” is defined by the “Metrology system,” with the aim to evaluate the injected products’ compliance. By last, the “Act” is the “Improvement plans.” Each of the above categories has its own strategies and recommendations and those are used to create a diagnostic tool. The diagnostic tool is a “Yes / No” survey, where each strategy is a question to answer. The tool is used to determine the BPMs application level in the companies analyzed.

Evaluation of GMP in a Colombian region

Nine representative companies from a Colombian region were selected to evaluate the compliance of their manufacturing practices. These companies have more than 300 injection molding machines, with a wide range of technologies, clamping forces, raw materials, equipment, and peripheral devices. To determine the manufacturing practices of each company is necessary to follow the chain production flow, from the raw material storage to the product delivery.

Measuring the SEC in a Colombian region

Seventeen injection machines were selected, and then, SEC was calculated. To make the selection representative, the researchers focus on injection processes avoiding disruptions in energy consumption and considering their output capacities (kg/h), technical specifications (plasticizing capacities and clamping forces), and type of processing materials. To calculate the SEC is necessary to measure the power consumption for each injection machine and their productivity. To measure the power consumption, a three-phase energy quality analyzer was used. A Fluke 430E was adjusted to measure one sample per second. To measure productivity, a calibrated scale was used to measure the weight and a calibrated chronometer to measure the cycle time.

With a simple calculation, it is possible to estimate the energy consumed per cycle (kWh). The area under the curve of power consumption vs cycle time is the energy consumed in that cycle. So, the SEC is the ratio between the energy consumed by cycle (kwh) and the weight (kg) of the injected product.

Results and discussion

Measuring the implementation of GMP in the plastic injection sector in a Colombian region

Figure 2 shows the overall score of the evaluated companies. This score is the GMP percentage reached by each company. These values showed a maximum of 72% and a minimum of 35% and the average value was 56% (dashed line), which shows a wide variation of the values and indicates a high improvement potential. The wide variation reveals that every company has its own limitations in order to achieve a better manufacturing practice, but Fig. 2 could be used as a benchmarking tool for these and other companies, in order to compare their selves about their own performance.

Figure 3 shows the diagnostic tool score by each category. The category that exhibited the most progress was “Quality control and customer management” (78%). The categories that exhibited the least progress were “Plasticizing unit” (44%), “Periphereal equipment” (49%) and “Molds” (51%). These low values could be due to the Colombian manufacturing industry that has presented low automatization indices, along with a strong deceleration of machinery imports for the plastics sector in the last 6 years (Hurtado and Mejía 2014). A sign of this is the low innovation rate in the sector in the last 5 years (Amézquita 2008; DANE 2017).

Regarding the “Plasticizing unit,” the results indicated that the most relevant aspects to be improved were stablishing a screw replacement policy and having spare screws and tips. Concerning “Peripheral

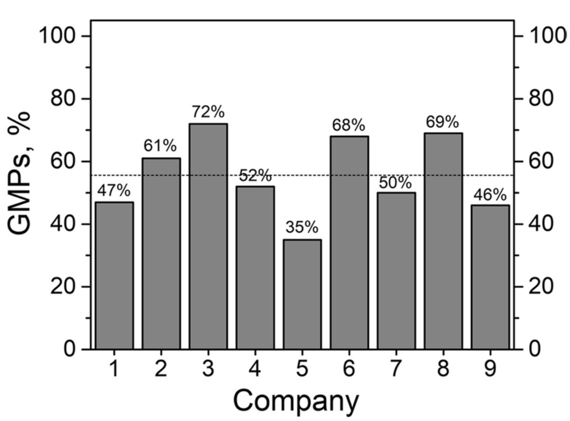

Fig. 2 Overall score of the companies under evaluation

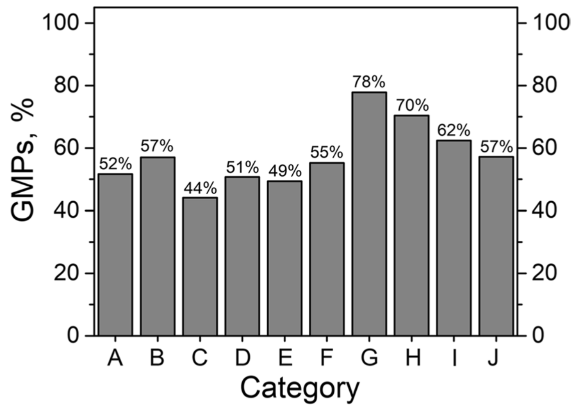

Fig. 3 Overall score by category for all companies under evaluation. (A) Storage and resin handle. (B) Drive units. (C) Plasticizing unit. (D) Molds. (E) Peripheral equipment. (F) Production planning. (G) Customer management. (H) Occupational health. (I) Maintenance plans. (J) Metrology system

equipment", the most relevant aspects to be improved were the use of new dehumidification technologies, creating a program to rationalize the use of raw material and eliminate air leakages. The "Metrology" category reveals a particular situation, since no company uses a pressure sensor in the mold cavity, although this is one of the main trends in the injection molding sector, to control the final product and process. In the same category, it was found that measuring and controlling specific energy consumption are a weakness in all the companies under analysis, despite the crucial importance of this factor for resource use optimization.

Determination of SEC's behavior in the region

Table 1 presents the power measurements of each molding machine. It also included the power required by each injection cycle, output, injected weight, cycle time, material, and SEC calculations. A relationship between injected weight and cycle time can be observed. In this process, the greater the injected weight and thickness, the higher the power requirement, and the cooling time is also noticeably affected.

Another result observed in Table 1 was the SEC behavior did not show a direct relationship with the polymer material injected. In addition, a longer cycle time does not mean a greater SEC. SEC is related to required power and product injected weight.

On the other hand, it was observed a relationship between SEC and the machine output, as shown in Fig. 4. Figure 4 shows how the SEC changes when the machine output (productivity) rises. Each value

Table 1 Power measurement results, injection parameters, and SEC calculations of each one of the 17 injection molding machines

Machine number	Power required (kW)	Output (kg/h)	SEC (kWh/kg)	Weight (kg)	Cycle time (s)	Material
1	21.15	8.19	2.58	0.06	25.00	PE
2	7.03	15.32	0.46	0.15	36.00	PE
3	24.45	38.43	0.64	0.43	40.00	PE
4	19.60	26.60	0.74	0.13	18.00	PET
5	9.21	20.91	0.44	0.12	21.00	PP
6	15.52	41.57	0.37	0.61	53.00	PP
7	4.95	2.43	2.04	0.01	20.00	PP
8	30.79	53.63	0.57	0.73	49.00	PP
9	20.74	22.90	0.91	0.37	58.00	PP
10	112.59	101.25	1.11	1.13	40.00	PP
11	23.61	3.13	7.54	0.02	23.00	PP
12	85.85	186.64	0.46	2.45	47.18	PP
13	13.30	27.3	0.49	--	--	PP
14	41.23	60.69	0.68	0.94	56.00	PS
15	9.68	24.81	0.39	--	--	PS
16	11.80	31.24	0.38	0.30	34.00	PS
17	31.07	27.15	1.14	0.36	48.00	PS

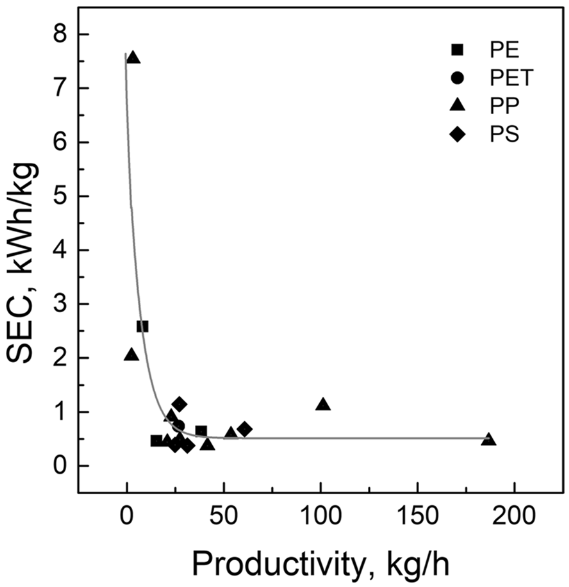

Fig. 4 SEC behavior at productivity changes, for each material injected

in Fig. 4, corresponds to each analyzed machine from Table 1 and they are an average of five cycles analyzed. The same behavior presented in other studies was observed (R. Kent 2008b). When the machine output rises, the SEC drops. This does not mean that the power requirement or energy consumption decrease. On the contrary, when the output increases so does the power requirement, but the amount of energy consumed by the transformed kilogram (SEC) declines. This means that it could be appropriate for an injection system, to operate at high production levels (output), because it would be more energy efficient.

SEC is related to power required and injected weight. Based on this, several GMP strategies could be used: Optimized efficiency motors, sequential and variable-stream hydraulic systems, optimized heating and cooling conveyor belts, adiabatic heat banding, high-performance molding screws, among others. Therefore, to achieve high production levels, the injection molding screw should be kept in optimal conditions. Additionally, process and mold simulation tools should be used to avoid reprocessing, and the energy consumed in transformation and equipment should be managed.

Related to the cycle measuring, it was observed in some cases, variations from cycle to cycle. These

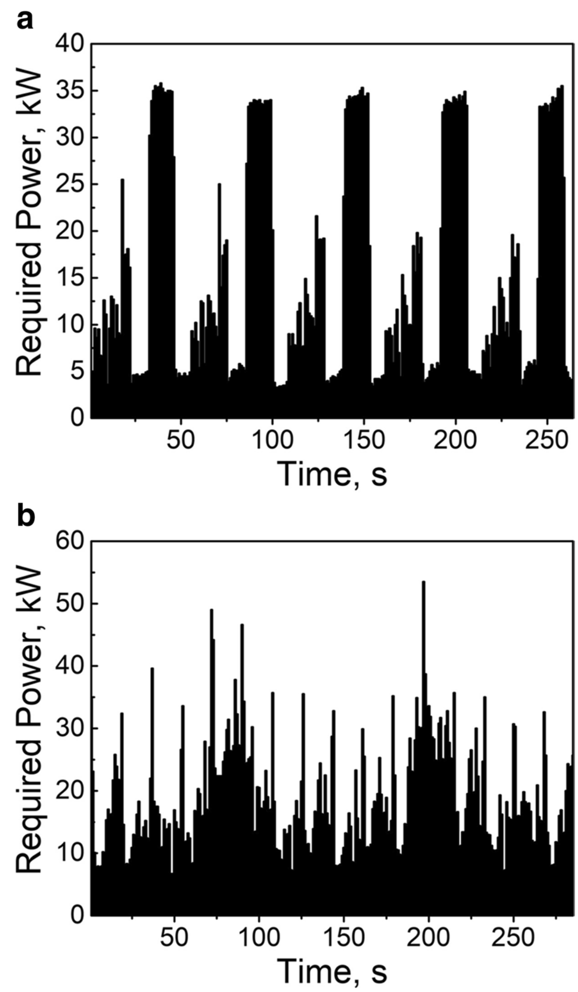

Fig. 5 **A** Required power profile for a process with low variability. **B** Required power profile for a process with high variability

variations affect the repeatability, energy consumption, and injected product weight and size. Figure 5 shows two spectrums regarding the injection cycles variability and they are the power required profile vs time. Figure 5A shows a process with low variability (1% between cycles). Figure 5B shows a process with high variability between injection cycles (28%). The variability was calculated with the relation between the standard deviation and the average power required. It was observed that when the process has low variability in the power required profile, the injected product presented very good dimensional tolerance and low weight variability. On the contrary, when the process variability is too high, the injected weight and the SEC are noticeably affected.

Controlling the variation between cycles is the result of several manufacturing practices. Ensuring the "homogeneity of the raw material," "using suitable mixing and dosing technologies," and the "elimination of dusts and regrinds" reduces the variation from cycle to cycle. Additionally, using "molding screws in the best conditions" avoids pulsations in the material metering. "Training the staff in injection parameter and measurement systems" is another method to diminish such variations.

Other GMP to be implemented is the estimation of the base and variable load to estimate the process goal line. The base load of the system depends on the operation downtimes when the machine-mold combination is still active but not in production. The variable load is related to the operation or process inefficiencies. Figure 6 plots the required power vs output (productivity) for each machine. The continuous line is the trend line using lineal regression. The trend line equation is showed in Fig. 6. The equation slope refers to the variable load, this is the average SEC of the machines, and the equation intercept refers to the base load. As a result, the base load for the machines under study was 6.72kW and the variable load is 0.53 kWh/kg.

Related to Fig. 6, all the values above the trend line are considered to have the greatest improvement potential; proof of this is that there are other machines with the same productivity that require the same amount of power, or even less, to achieve the same productivity. There is a particular value in Fig. 6, noticeably far from the trend line (112.59 kW). Such machine requires an excessive amount of power for given productivity. Specifically, this machine-mold combination reveals an oversized machine used to inject the product, i.e., the equipment was way too big (900 tons clamp force) and requires 112.59 kW to inject a small product (1.13 kg).

The base load could be greatly improved by implementing some GMP, such as "planning production." On the other hand, improving the variable load implies training the staff and a good selection of injection molding parameters.

To establish the goal line, the values above the trend line should be eliminated and data should be replotted, as shown in Fig. 7. The base load of the machines under study could be reduced to 1.80 kW and the average SEC (slope of the trend line) to 0.45 kWh/kg. Figure 7 shows three scenarios: there are processes above, on, and under the trend line. The displacement of the values from the trend line may be a result of the achieved percentage of GMP implementation showed in Fig. 2.

Finally, the Company 3 was selected in order to evaluate the GMP proposed in this work and their potential to improve the SEC in their injection

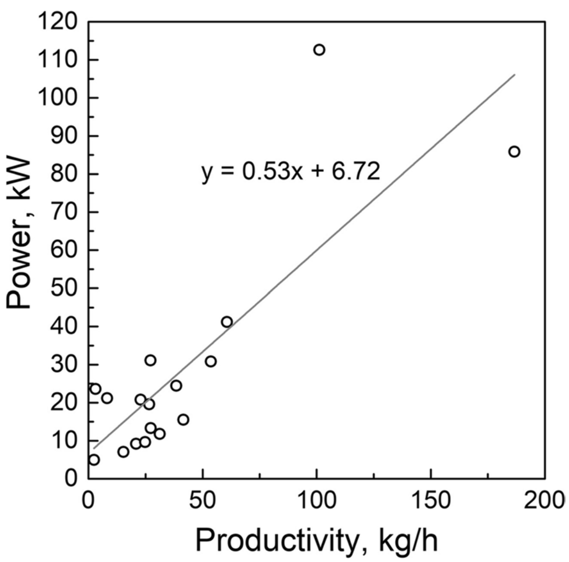

Fig. 6 Plot of power required vs output for each process

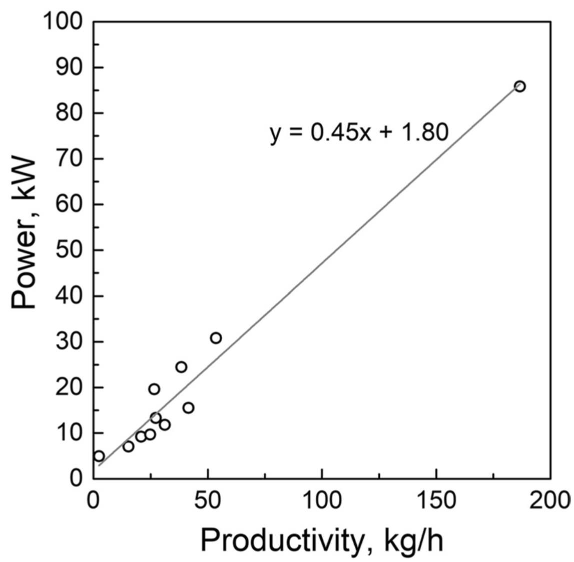

Fig. 7 Adjusted plot of power required vs output for each process

molding process. This company was selected because it shows a better overall score in GMP application and improving their manufacturing practices implied a bigger challenge.

Table 2 shows the GMP categories and their impact on SEC. This impact level was estimated and validated by following up on each category in this company. More information about each developed strategy is shown in Supplementary Material.

After a thorough evaluation, it was possible to estimate how the SEC was affected by the GMP categories. It was observed that all the GMP contribute to improving the SEC with different significance, ranging the relevance from 6% ("Resin Storage" and "Occupational Health") to 14% ("Plasticizing Unit" and "Drive Unit"). It was observed that plasticizing and drive units are the most relevant categories to impact the SEC in Company 3, and this affects the plant power requirements.

On the other hand, as it can be seen in supplementary material, resin storage affects the homogeneity, humidity, and quality of final injected product, which affects the compliant product and in turn the SEC. Additionally, the resin handle, in large plants could be a more important category, especially if electrical motors or combustion engines are used to transport the raw material, rising the power plant requirements.

Conclusions

In this research, a comprehensive framework to study the specific energy consumption (SEC) through the best manufacturing practices (BMP) in polymer companies was shown. It was possible to observe in a depth way, the factors that affect the SEC in the polymer injection industry, with the potential to reduce production costs and mitigate negative environmental impacts in polymer processing companies. The proposed method is applicable both to characterize existing transformation systems and to generate strategies that allow efficient and sustainable production processes.

Table 2 Estimated impact of each GMP category on SEC in Company 3

PDCA	Category	Impact on SEC
Plan	Resin storage and management	6%
	Occupational Health	6%
	Production scheduling	10%
	Customer management	6%
	Maintenance	10%
Do	Peripheral equipment	12%
	Plasticizing unit	14%
	Drive unit	14%
	Molds	13%
Check	Metrology	9%

A diagnostic tool was created to determine the state of polymer injection industry, regarding GMP. Such tool was validated by studying the GMP implementation at 9 companies in a particular Colombian region. Great improvement potential was found for "Plasticizing unit," "Drive unit," "Measuring system," and "SEC measurement and control" categories.

It was observed that SEC measurement is a good tool to evaluate the GMP implementation in a polymer injection plant. A SEC evaluation was conducted in 17 injection polymer processes of these companies. The results constitute a first stage and provide these companies with a baseline to compare their processes, in order to regulate their manufacturing practices and energy losses during their workflow.

The authors found that the SEC measurement range of injection molding system in the particular Colombian region was between 0.37 and 7.54 kWh/kg. Nevertheless, a single SEC value cannot be established for all the injection molding systems because it depends on the injected weight, the machine output (productivity), and each mold-machine-material combination. However, it was found that an average SEC for the injection molding process could be between 0.45 and 0.53 kWh/kg, as shown in Figs. 6 and 7.

A relationship between the GMP and SEC was found. Furthermore, the correct implementation of GMP can reduce the SEC indicator.

All the machines' performance in this study can be improved, and this is confirmed by the fact that there are other machines that have the same output (productivity), less SEC, and lower power requirement. The Plan, Do, Check and Act cycle (PDCA) shown in Table 2 could be applied to improve the process performance.

The SEC indicator has a strong dependency on the peripheral equipment, the plasticizing unit, the drive unit, and mold selected and, in fact, has a strong dependency on the "Do" of the PDCA Cycle as shown in Table 2. This is a demonstration that the proper tailoring of the machine size, raw materials, and mold is a key to reduce the SEC indicator. But, in order to apply GMP to reduce SEC without major interventions on the hardware, the maintenance program and the production scheduling are two important factors to be considered.

This study did not observe a relevant relationship between SEC and injected material. But the authors recognize that this is a future work to do.

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Declarations

Conflict of interest The authors declare no competing interests.

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