TÉCNICO LISBOA

Optimization of the manufacturing process of hollow glass

Zorina, Anastasiya[a,b]; Aguiar, Fernando[b]; Gonçalves, Clara[a]; Amado, Conceição[a].

[a] Instituto Superior Técnico, Avenida Rovisco Pais, 1, 1049-001, Lisboa Portugal

[b] Rua Vice-Almirante Azevedo Coutinho, 2700-843 Venda Nova, Lisboa, Portugal

Abstract

This work emerges as a response to a challenge posed by the *BA glass* plant - the implementation of the *Best Day* project in a production line. The *Best Day* project aims to monitor, in real time, all the process variables in a selected production line and to register all the product parameters, to characterize the *Best Manufacturing Day* for a study article. The *Best Manufacturing Day* of an article corresponds to the day when the highest production was recorded, with no critical defects and customer complaints (a *posteriori* registration).

The aim of this project was to establish the process variables that require an increased control over the other variables, in order to obtain a more efficient production. To accomplish this objective, a statistical study was carried out in which linear correlations between the explanatory variables and the response variables of interest were established, followed by the modeling of the variables to make a statistical inference using *SPSS*.

It was concluded that the variables related to the furnace, namely some temperatures (T1102 e T1203, near to the throat of furnace) as well as the air /gas ratio used have strong to moderate *Pearson* correlations with the response variables. The same is true of manufacturing variables related to the shape of gout, namely parameters that pertain to plunger. The formation of a perfect gout is the primary condition for achieving a conformal glass container.

Key-words: Optimization, Best Manufacturing Day, highest production, critical defects, *Pearson* correlations.

1. Introduction

The centenary company "Barbosa e Almeida", current *BA Glass*, was founded in 1912 by partners Raul da Silva Barbosa and Domingos de Almeida. It began its activity in 1930 in Campanhã. In 1971 the first machine of independent section (IS machine) was installed, that favored the productive capacity thought its automazation. The BA group has evolved as it can be seen on the next figure. Nowadays the group has 12 factories located in 7 different countries such as: Portugal, Spain, Poland, Germany, Greece, Romania and Bulgaria

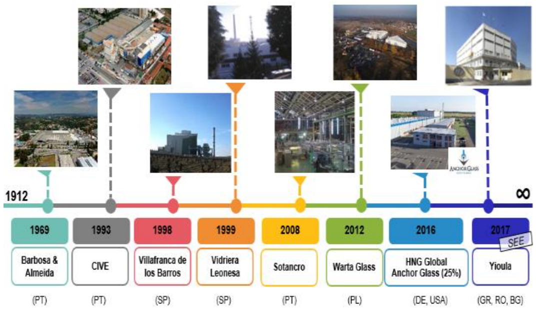

Figure 1 - Evolution of BA Glass's constitution over time.

BA Glass produces more than 8 billion bottles per year in 11 colors. With a total of 3,800 employees, BA distributes glass packaging in more than 80 countries worldwide. Its current turnover is around € 780 millions [1].

Competitiveness in the glass industry has been increasing and producing large scale, low cost and no defects is a requirement. Thus, the continuous improvement of the process has been increasingly focused.

This project serves to extend the optimization of the hollow glass manufacturing process through the implementation of Best Day at *BA Glass*, whose pioneering plant is Venda Nova (Amadora).

2. *Best Day* Project

The project aims to determine the best day of manufacture, which is obtained when a greater useful quantity of an article is produced, without critical defects, and finally without complaints by the client in *posteriori*. The project involves a record of all process variables from the furnace zone to the cold end. By keeping a record of all process variables in the manufacturing process, we are able to compare the production of any given day, amongst the several factories within the group.

The implementation of Best Day began with the selection of an article, followed by the study of a stable production line, to establish the procedural variables that most disturb the product parameters that mark the *Best Day*. The chosen article was the 4630S037 glass bottle of 0.7 cL, bottle produced in I.S. machine through the Blow-Blasted process.

The response variables studied are i) KCR (key Cavity Rate, related to cadence of I.S. machine and weight of vitreous gob); ii) useful production (production ready to pack) iii) critical defects (those which endanger the health of consumers).

Figure 2 – Chipped finish as an example of critical defect.

3. State of the art

Process for the manufacture of container glass

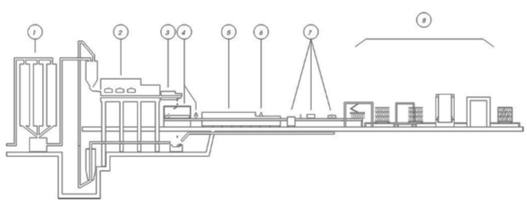

Figure 3 – Flow diagram of the manufacturing process of the packaging glass. 1 - Composition; 2 - Fusion; 3 - Thermal conditioning; 4 - Molding and hot end; 5 - Annealing; 6 – Cold end; 7 - Inspection; 8 – Packing.

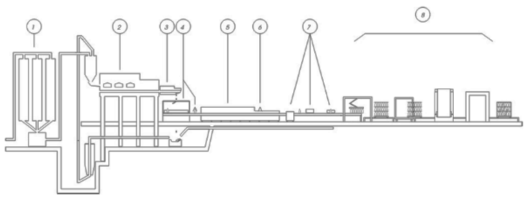

Figure 3 illustrates the glassmaking process.

Raw material zone

BA Glass receives daily the necessary RM (raw material) to produce the glass containers, each of them being stored in its silo.

Table 1 - Composition of the raw material used to manufacture the container glass in the furnace under study.

Raw material	Function	Composition (%)
Sand	Former	77,4-36,3
Na_2O	Flux	23,5-10,9
K_2CO_3		0,5-0
CaO	Stabilizer	21,1-9,4
Al_2O_3		4,3-0
Slags		1-0
Na_2SO_4	Additives	0,3-0
C		0,01-0
$ZnSeO_3$	Dyes	0,002-0
Fe_2O_3		5,8-0
White cullet		38,6-0
Green cullet		2,6-0

The specification of the raw materials (Table 1) depends on the glass to be produced, but also on the furnace to be fed. In the present study, oven 3 was used to produce white glass during the article in study manufacturing campaigns. The material used have different functions[2][3]:

- Formers, they confer vitreous structure, being a classic example the Silicon Oxide (Tf - 1723ºC), present in the sand.

- Fluxes, composed of Sodium Oxide and Potassium Carbonate have the purpose of lowering the melting temperature of the glass.

- Stabilizers, contribute in stabilizing the vitreous mass, after its fusion. So Calcium Oxide and Aluminum Oxide are added to enhance the chemical stability of the glass. Slags are materials resulting from the contact of the raw material with the refractories of the furnace. These are used to make the process profitable.

- Additives, composed of fine carbon and Sodium Sulphate favor the elimination of dissolved gases (NOx, SO2, CO2 e CO) in the vitreous mass, which cause nonconformities of the final product.

Broken glass, called a cullet, is added to reduce the melting temperature of the mixture, thus reducing energy consumption.

It should be noted that the ensilage zone operates continuously and the furnace can't stop unless the material to be vitrified solidifies.

Fusion zone

The furnace is regenerative [3][4], powered by natural gas and air and is boosted by electric power which contributes 40% to the melting zone and 60% to the tuning zone.

It is composed of several different parts [5], as is explained in where there is:

- Recuperator/Regenerator: formed with several refractory parts, such as a beehive comb, with several and is heated by the passage of flue gases. At regular intervals (20-30 minutes - called the inversion time) the burn is cut off and the regeneration chamber becomes the combustion air duct.

- Melting zone: where the reactions of transformation (dissolution, decarbonation, among others) of the raw materials take place.

- Tuning zone: responsible for the elimination of the dissolved gases through the addition of additives and the existence of bubblers.

- Working tank: responsible for homogenizing the vitreous mass through influence of promoted temperature. It serves as a connection to the glass distribution channels, forehearths.

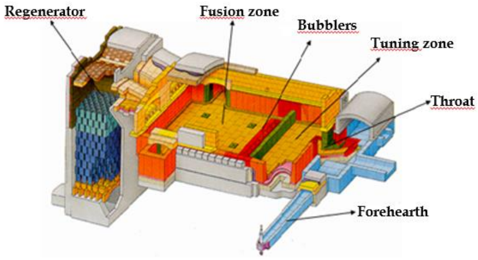

Figure 4 - Regenerative Furnace Scheme.

It is essential that there is a balance between the residence time of the glass mass and the convex forces of the furnace for the thermo-chemical homogenization of the furnace, without the existence of a blisters or blasts, for the final product to conform.

Fabrication zone

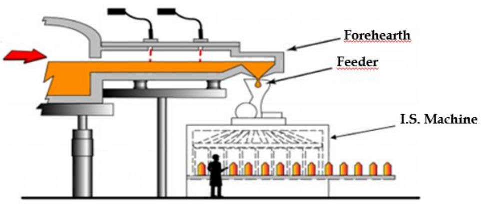

Figure 5 - Flow diagram of the glass along the manufacturing zone.

This, next to the zone of the furnace, is one of the hottest zones of the process (Figure 5). It is here that the molten vitreous mass passes through the conditioning channel, forehearth, where the glass leaves the furnace throat at around 1150°C [6] and is consequently heated /cooled to reach the conditioning zone, which feeds the glass, through the feeder, to IS machines (independent section machines).

The feeder consists of a combination of the refractory tube that is located at a certain height that rotates at a certain speed and in clock wise direction that allows the flow of the glass to be homogenized [7]. With the aid of a plunger the glass is pushed down and the vitreous gob drops vertically into the distribution channels [2] [3]. The distribution channel is lubricated with water and oil to reduce friction (as shown in Figure 6).

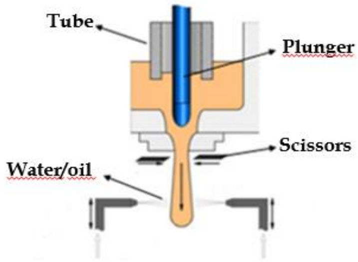

Figure 6 – Feeder mechanism.

The glass drop is therefore deflected to the blank section of the IS machines. The process used for its formation is Blow-Blow, in which the blank provides an outline to the final product as well as forming the shell thereof, providing adequate heat transfer from the glass to the mold to ensure a certain viscosity [8]. The finish mold as the name itself, contributes to the final printing of the packaging. The glass containers after the exit of IS machines undergo a hot surface treatment to guarantee their mechanical resistance.

Cold zone

After deposition of the hot end, the glass containers are subjected to the relief of stresses by annealing lasting no longer than 30 minutes. Then is applied cold end treatment to improve the strength of glass containers and reduce scratches and cracks during filling and transport. Finally, the glass containers pass through inspection machines that allow the selection of the bottles according to the desired specification.

Statistical analysis of process of production of glass containers

It was verified that several studies related to glass were made. Statistical tools, such as *R*, which is a programming language as well as an integrated development environment for statistical and graphical calculations, like *SPSS* was used in the analysis multivariate data, aiming to classify sites from medieval glass samples [9]. The origin of glass has been established through *Pearson* correlations [10] that provide the linear relationship between several constituents of glass composition. The r_{12} (*Pearson* coefficient) can take values between -1 (meaning that if one variable decreases, the related one increases and vice-versa) and +1 (meaning that if one variable increases, the related one increases too), whose interpretation of the values is explained in Table 2.

Table 2 - Classification of the force between the *Pearson* correlation values.

r_{12}	Correlation strength
|0,9|- |1|	Very strong
|0,9|- |0,7|	Strong
|0,7|- |0,5|	Moderate
|0,5|- |0,3|	Weak
|0,3|- |0|	Negligible

It has been pointed out that several glass-related modeling studies have already been carried out, within which are the projects related to heat transfer to simulate the behavior of the raw materials in the melting and refining zone, based on CFD (Computational Fluid Dynamics) [11][12]; optimizing of the reaction zone and simplification of hydrodynamics using CFD.

However the literature did not reveal any project that was related to a global review of the glass manufacturing process, from a statistical point of view. On the other hand, no preferential analysis was also performed on the variables that need constant monitoring so that there is no specific type of defects or greater quantity of articles produced.

After establishing correlations between procedural variables and responses, a mathematical modeling was performed using linear and logistic regressions in *SPSS*[10].

4. Results

Choice of procedural variables for input in *SPSS*

The procedural variables collected were obtained through several documents provided by the different areas such as those of the furnace, the manufacturing and the cold zone. It should be noted that the fabrics of the main glass bottle, 4630S037 of 0.7 cL, are diverse and summarize a total of 241 days of manufacture, starting from 22-7-2015 until 8-1-2018. The last manufacture of this bottle, from 1-3-2018 to 15-3-2018 was used as predictive validation of the models obtained in regression analysis.

When the variables of the manufacturing process were surveyed, it was found that the registration of all the days of manufacture was not always verified. A screening was done, where variables were found that lack record of observations or that are always constant, thus not having any variability. It should be considered that it is necessary to have between 10 and 20 observations for each analyzed variable so that the statistical inference is significant. Some furnace temperatures lacked a constant register. On the other hand, the same was observed with the gaseous emission control variables, which are indicative of the combustion quality in the furnace. The time of gob drop in the distributors also lacks the record history. The blank, final mold and counterblow temperatures have a small number of registers (81 observations recorded over 241 days of manufacture analyzed) which precludes their analysis, although it is known that they play a key role in the distribution of the glass. In addition to the recording of tool temperatures, the glass drop conditioners are also missing, namely their speed, length and diameter. It is known that gob must be as short and fat as possible, cylindrically with rounded tips, having a relationship between its length and diameter of 2.8. The forehearth temperatures also have missing records, where in 241 days of manufacture, there are only 66 observations, again an insufficient number of observations for analysis to be possible.

The variables are arranged in the order of the procedural zones, in which the oven variables are initially presented and finally the ones that are used in the cold zone. The furnace variables relate to the different impending temperatures, the energy consumption and the raw materials used. It also includes some quality variables. Several variables related to the tool used in the I.S. machines, which have a direct influence on the formation of gob, are considered

Some of the variables presented here have multicollinearity, that is, they are dependent on each other, with a correlation force greater than |0.8|. These cannot be embedded in the regression models.

Table 3 - Variables included in the statistical analysis of the 4630S037 bottle of 0.7 cL

Included				
T1102	SP_NN	Pump_PRESS	Plunger_course	Balance
T1203	PV_NN	Pump_TEMP	Plunger_height	Compression
T_Wall	NV	Control_NO_x	Degree_plunger	Parison_cooling
T_Crown	Inversion	% Raw materail	Scissors_Crossing	Final_blow
T_Top	Cullet_perc	Sampling weight	Scissors_course	Piloting_pressure
T_Base	Pull	Density	Water_consumption_scissors	Internal_pressure
PI_mm_H2O	Positions of boosting	Seeds	Water_pressure_scissors	High_air_pressure
EPI_perc	Pot_AB / Pot_CD	Blisters	Scissors_cut_time	Low_air_pressure
EPI_N	Pot_tot	Blisters/kg	Scissors_initial_position	Pushers_velocity
Gas_ Nm3_h	VOLTS_AB/VOLTS_CD	Dom	Scissors_central_position	Freq_HotEnd
Gas_perc	AMPS_AB/AMPS_CD	Shine_perc	Water/oil_scissors	T_Hotte
Gast_PresBar	VOLTS_TA a VOLTS_TD	Purity_S_perc	Machine ventilation	L_T_ColdEnd
AirComb_Nm3_h	Rotations_AB/Rotations_CD	X_Perc	Pressure of ventilation	C_T_ColdEnd
AirComb_of_perc	OIL_T	Y_Perc	Temperature	R_T_ColdEnd
AirComb_Ventilador_N	Count_kW_Day	Height_Tube	Dead_plate_ventilation	ColdEnd_degree_L
Air_Gas	Count_TOT_kWH	Torque_Tube	Vacuum	ColdEnd_degree_C
Manual Reading of glass	Pump_N	Velocity_Tube	Rupture	ColdEnd_degree_R

Pearson correlations of procedural variables with response variables

Table 4 - *Pearson's* correlations obtained between the procedural variables and the useful production of 4630S037.

Pearson Correlations							
T1102	0,60	Plunger_course	-0,48	D4	0,31	Y_perc	-0,21
Count_TOT_kWH	0,59	Degree_plunger	0,48	NV_left	-0,40	PI_mm_H_2O	0,21
Pump_PRESS	0,51	Sampling weight	0,47	T1203	0,47	Tbase_right	-0,20
Pump_TEMP	-0,53	Pressure of ventilation	-0,46	Gas_Nm3_h	-0,37	NV_right	-0,17
Cadence	0,64	Vacuum	-0,38	Tbase_left	-0,36	Slags	-0,17
KCR	0,68	Rupture	0,46	Seeds	0,37	Residues	-0,20
Sodium_Sulphate	0,50	Internal_pressure	0,45	Dead_plate_ventilation	0,28	L_T_ColdEnd	0,20
Pushers_velocity	-0,51	Water_consumption_scissors	0,45	Control_Nox	0,28	Freq_HotEnd	-0,22
Plunger_height	-0,53	Scissors_course	-0,44	T_topo	-0,27	Balance	-0,18
Scissors_central_position	-0,51	AirComb_Nm3_h	0,35	Height_Tube	0,27	Density	0,17
Torque_Tube	0,54	Air/gas_right	0,43	C	0,26	Scissors_Crossing	0,14
Pushers_velocity	-0,51	Air/gas_left	0,38	Compression	-0,25	T_Crown	-0,14
Size tube guide	0,54	C4	0,48	Funnels	0,25	Temperature	-0,14
Piloting_pressure	0,57			Water/oil_scissors	-0,22	Blisters	-0,14

As it observed in Table 4 the useful production has moderate correlations with some furnace parameters, according to Table 2. This variable increase when there is an increase in the energy consumed, in T1102, T1203 and Sodium Sulphate used, which is expected since when more toner is used, it is because there is more raw material to put in the furnace so T1102 increases and consequently the energy consumed in the oven is higher. However, since there is more useful production, the use of electric boosting tends to be greater as well. Thus, the cooling thereof is increased, whereby the temperature of the pump decreases and the pressure of the pump increases to cool the electrodes.

In terms of qualitative parameters of the container glass, it is verified that the variable analyzed increases with the increase of the seeds and with the reduction of blisters. The blisters tend to appear in larger quantities when proper control of the furnace, i.e. the tuning zone, is not done.

It is natural that the KCR and the cadence increase with the increase of the useful production, because there is a larger glassy mass to distribute in the independent sections and these parameters are intrinsically interconnected. The same applies to weight, parameter strictly related to the variables mentioned above.

Before analyzing the parameters related to the formation of gob, such as the height, course and phase of the plunger, it is fundamental to understand that these parameters have a direct influence on the formation of gob. The perfect gob is achieved with homogenized glass flow and correct temperature (at the outlet of the furnace throat it must be at 1150°C and the inlet of the blank in a range between 465°C-475ºC) so that the distribution of the glass is as uniform as possible. The plunger phase (degrees) increases as the weight of the article increases, as its length also increases. If the length of the drop increases, the plunger height is decreased, so the correlation here is negative and correct. The stroke of the plunger decreases with increasing pull (consequent increase in useful production), thus there is variation in the weight of the drop or the cadence of the machine. It is necessary to ensure the ratio between length and diameter of 2.8 to have the perfect gob. It should be noted that no correlation is established between the conditioning variables of the glass and the subsequent temperatures in the different sections of the glass forming machine, which has a negative effect on the results mentioned herein. The above parameters are critical in the amount of glass injected, which interconnects directly with the temperature variations in the forehearth. It is highly recommended to the factory register these variables every day.

Considering the variables related to the cut of the gob, it is possible to examine that the amount of useful production increases when these decrease both its course and its central position, that is, when its opening has a lower value. This relationship is obvious given that when there is more quantity to be produced, the higher the speed of the machine, and therefore, the faster the movement of the cutting of the scissors. The water consumption in the scissors increases, as observed by the moderate correlation, which is predictable since with the increase of the useful production also increases the need of quantity of water to lubricate the same ones. The ratio of water/oil used in the scissors, in order to decrease the existing friction and to correctly guide the glass gob, decreases with increasing useful production. This relationship is spurious because when more glass is produced, a greater fraction of lubricating agents is required.

The linear associations obtained in Table 5 are similar to those of the useful production, however there are differences in the strength of the correlation force. The relationships established here are still stronger, that is, the ones that are common that were moderate became strong and the weak ones became moderate.

Table 5 - *Pearson* correlations obtained between the procedural variables and *KCR* of 4630S037 of 0.7 cL.

***Pearson* Correlations**							
Count_TOT_kWH	0,81	Pump_TEMP	-0,50	Blisters	-0,26	Rotations CD	0,22
Torque_Tube	0,73	Sodium_Sulphate	0,54	Peso	0,47	C	0,28
Plunger_course	-0,80	Plunger_height	-0,56	Gas_Nm3_h	0,33	Feldspar	0,13
Degree_plunger	0,76	Dead_plate_ventilation	0,47	AirComb_Nm3_h	0,38	Slags	-0,16
Scissors_course	-0,75	Vacuum	-0,48	Air/gas_right	0,46	External white cullet	-0,15
Size tube guide	0,82	Water_consumption_scissors	0,41	Air/gas_left	0,37	Manual Reading of glass	0,21
C4	0,70	Water/oil_scissors	-0,38	Tbase_left	-0,43	Tbase_right	-0,19
Rupture	0,69	Temperature	-0,38	ColdEnd_degree_L	0,29	NV_right	-0,18
Pressure of ventilation	-0,62	Control_Nox	0,41	Blank utilization rate	0,31	Final blow	-0,17
Internal_pressure	0,63	D4	0,39	Plunger_height	0,39	Deflectors size	-0,17
Pushers_velocity	-0,61	Pump_PRESS	0,43	Density	0,24	Rejection_MIL	0,16
T1102	0,59	NV_left	-0,38	Rotations AB	0,27	Hot_End_Perc	-0,14
T1203	0,52	Seeds	0,38			T hotte	-0,14

This fact is relevant to the conclusion that the useful production is obviously correlated with the *KCR*.

Spurious correlations, related to RM, that infer the use of C (fine coal) and feldspar as enhancers of KCR increase, which is not necessarily true. The same applies to the rejection percentages on inspection machines, which are contradictory and therefore negligible.

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Table 6- *Pearson* correlations obtained between the procedural variables and the categorized critical defects of 4630S037 of 0.7 cL

Pearson Correlations							
Degree_plunger	0,36	Air/gas_right	0,24	Mould final rate utilization	0,21	Water_consumption_scissors	0,16
Torque_Tube	0,36	Count_TOT_kWH	0,23	T1203	0,21	Pressure of ventilation	-0,16
Sampling weight	0,32	Internal_pressure	0,23	B4	0,21	Vacuum	-0,16
Scissors_central_position	-0,32	Rupture	0,23	Plunger_height	-0,21	E2	-0,16
Water/oil_scissors	-0,35	Atr_cal_colher_distribuidor	0,23	Seeds	0,20	B1	0,15
NV_left	-0,30	ArComb_Nm3_h	0,23	Freq_HotEnd	-0,19	D4	0,15
Scissors_course	-0,29	C4	0,23	KCR	0,18	Plunger_course	-0,15
Pushers_velocity	-0,27	NV_right	-0,23	T1102	0,17	Cadence	0,14
Pump_TEMP	-0,26	E4	0,22	C2	-0,17	Air/gas_left	0,14
Size tube guide	0,26	Dead_plate_ventilation	0,22	Green external cullet	-0,17	Y_perc	0,13
Hot_End_Perc	-0,25	Blank rate utilization	0,22	Piloting_pressure	0,16	Pumo_pressure	0,16

The critical defects were divided in two categories: those that take the value of 1 that correspond then to the occurrence of the critical defects and those that take the value of 0 that are in turn those that present the non-occurrence of the same ones, in the days of manufacture respectively.

The correlations obtained in Table 6 are like those obtained in the response variables previously studied. The useful production has a direct proportion with the KCR and so when the critical defects increase, they decrease. Although the associations obtained have the same sign at the level of the stipulated correlations, it is denoted that they have a smaller force. This is because, as already seen above, this type of defects is mainly generated by thermal factors and mechanical factors, which in turn are interrelated.

Modeling the response variables

Linear regression

The variables that were part of the prediction of useful production behavior were selected based on the associations/ correlations obtained. Its sorting was done through several methods introduced in SPSS, namely backward and forward. Due care was taken to choose variables that meet the following requirements: i) have greater linear association with useful production; (ii) does not present multicollinearity between the independent variables.

In the following figure the forecast of the useful production, during the manufacture in the month of March is presented.

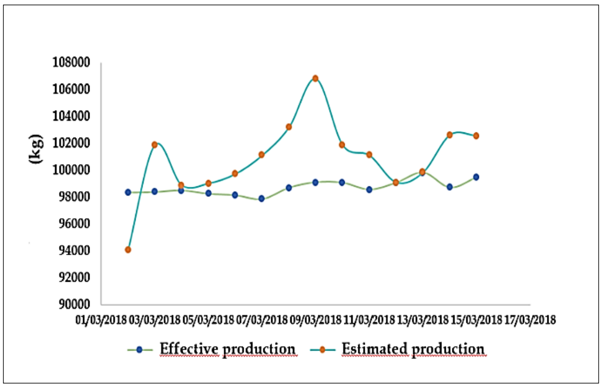

Figure 7 - Estimated and effective production expected during the March 2018 manufacture of 4630S037 0,7cL.

The furnace temperatures are predictive of the quantity of glass produced as well as its quality. The manufacturing variables, those that are related to the IS machine, particularly the plunger, are also predictive of the model. The model is statistically significant with relative errors less than 10%. The correlation coefficient is 0,714.

The variables related to KCR do not present autocorrelation with each other and the model obtained is statistically significant. Although the coefficient of determination is not a causal factor, it should be noted that it has a high value (0,946) (see Figure 8). Relative errors obtained are also inferior to 10%.

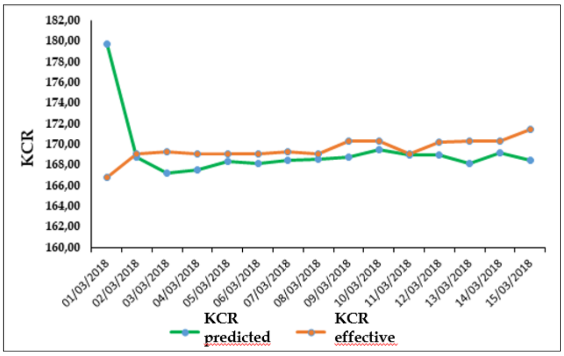

Figure 8 - KCR predicted and effective over the March 2018 manufacture of the 4630S037 of 0.7 cL.

Regarding the coefficients resulting from this analysis, it is concluded that these are statistically significant and are independent. It is noted that these refer again to the furnace, namely to the temperatures of the melting zone and tuning (T1102 and T1203); to the parameters of the boosting (C4); to the use of RM, more specifically to Silicon Oxide and white cullet and finally to the relation between the air/gas used in the furnace.

Logistic regression

In this model, the predicted success of the cases is 78.6%. It is noteworthy that the best classified cases refer to the days when there are no critical defects, which is expected since this is the largest number of days of manufacture. On the other hand, since the sampling of the days in which the critical defects occur is smaller (36 days compared to the 241 total), it is natural that the percentage of classification with the established forecast is lower. The pseudo R for this model is low (R^2 Nagelkerke: 0,422). As expected, the obtained model does not fit the actual data related to the critical defects because the key variables that relate to them have a lack of observations to be analyzed.

5. Conclusions

The linear associations established in relation to the furnace variables focus essentially on the oven temperatures, T1102 and T1203, and on the air/gas ratio used. Regarding manufacturing process variables, the most important are the parameters related to plunger, scissors (shears course and water consumption in scissors) as well as the sizes of the tubes used. All of the aforementioned parameters are central to the gob form, whose correct formation is one of the fundamental steps to produce a quality article.

In this first study it was possible to verify that the modeling in the critical defects does not have strong or moderate correlations, due to their origin. A second study is suggested in this variable, with due data related to the temperature distribution of the glass paste along both the forehearth and the independent sections of the machine.

6. References

[1] M. C. Gonçalves, “Vidros,” in *Ciência e Engenharia de materiais de construção*, IST Press., M. C. Gonçalves and F. Margarido, Eds. 2012, pp. 399–435.

[2] J. M. F. Navarro, *El vidrio*, Tercera ed. Madrid: ARTEGRAF, S.A., 2003.

[3] S. Tangjitsitcharoen, S. Ratanakuakangwan, M. Khonmeak, and N. Fuangworawong, “Investigation of Regenerative and Recuperative ecuperative Burners for Different ifferent Sizes of Reheating eheating Furnaces,” *Int. J. Mech. Aerospace, Ind. Mechatron. Manuf. Eng.*, vol. 7, no. 10, pp. 952–956, 2013.
[4] “Tipos de fornos e a sua construção.” Documentos internos da BA Glass, 2009
[5] H. Kai and N. Tobias, “Case Study: Gob Loading in a Glass Moulding Machine,” *Procedia CIRP*, vol. 39, pp. 203–208, 2016
[6] M. Kovačec, A. Pilipović, and N. Štefanić, “Improving the quality of glass containers production with plunger process control,” *CIRP J. Manuf. Sci. Technol.*, vol. 3, no. 4, pp. 304–310, 2010
[7] R. Penlington, M. Sarwar, and D. B. Lewis, “Application of advanced coatings to narrow neck press and blow plungers in the glass container industry,” *Surf. Coatings Technol.*, vol. 76–77, pp. 81–85, 1995
[8] V. Dillingerova, T. Vaculovic, E. V. A. Cerna, and V. Kanicky, “CLASSIFICATION OF ARCHAEOLOGICAL GLASS SAMPLES USING LA-ICP-MS,” pp. 855–860, 2017.
[9] R. A. Johnson and D. W. Wichern, “Applied multivariate statistical analysis.” 2007.
R. Beerkens, “Modeling of the melting process in industrial glass furnaces,” *Math. Simul. Glas. Technol. (Schott Ser. Glas. Glas. Ceram.*, pp. 1–93, 2002.
[10] M. K. Choudhary, R. Venuturumilli, and M. R. Hyre, “Mathematical Modeling of Flow and Heat Transfer Phenomena in Glass Melting, Delivery, and Forming Processes,” *Int. J. Appl. Glas. Sci.*, vol. 1, no. 2, pp. 188–214, 2010.
[11] M. H. Kutner, *Applied Linear Statistical Models*. 2005
[12] D. Files *et al.*, “IBM SPSS Statistics 23 Part 1 : Descriptive Statistics Downloading the Data Files,” pp. 1–18, 2016