Modelling Productivity Using the Structural Equations Method – A Case Study of Electrical Arc Furnance (EAF)

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***Abstract*— The production process for steel manufacturing is sometimes very complex, due to the necessarily synchronized interaction of all the equipment that makes it up and the multiple variables involved. The aim of this work is to develop a model of the steel melting process in an electric arc furnace (EAF), in order to evaluate the variables that influence productivity. This model consolidates the interaction of operational parameters, metallurgical variables, restrictions regarding the installed capacity of the equipment and operational availability. By means of the structural equations modeling methodology (SEM) the critical variables that have a direct relation with productivity were determined, these variables are the metallic load and the steel casting temperature. Based on the results obtained, the mathematical model that defines the process was determined, which was later compared with the pertinent industrial data, presenting satisfactory results.**

***Index Terms*—Electric arc furnace (EAF), metal scrap loading, casting temperature, steel, modeling, process, productivity.**

I. INTRODUCTION

In 1856 the british engineer Henry Bessemer developed the Bessemer process for steelmaking; later he perfected the process in order to reduce production costs [1].

Steel is an important material necessary for social and economic development [2]. Therefore, steel production is a key factor for the development of modern society [3]; and it is probably the most important building material of today [4].

The steel industry is the second largest in the world after the oil and gas industry, with a turnover of approximately 900 billion dollars [5]. Ecuador also produces steel in the following steel plant: Andec, Adelca and Novacero, which concentrate the total production of reinforcing steel for reinforced concrete structures.

The manufacture of steel is divided into several stages, being the process of fusion and refining the most critical; most of the elements are adjusted through additions of materials, mainly ferroalloys, however the carbon is adjusted through the injection of gaseous oxygen of high purity. The refining process consists of the chemical adjustment of all its elements with an accuracy of hundredths of a percentage, and even lower values, and is carried out at high temperatures, above 1400 °C [6]. Due to the complexity of the process combining heat and mass transfer, phase changes of the material, prediction of technological parameters and optimization of the process are usually done through empirical correlations [7]. Correct design and adjustment is therefore a task that requires a great deal of knowledge of both the different phenomena involved and their interactions [8].

It has been proven that some parameters such as the electrical regime and the dosage of the charge to the furnace contribute directly to the performance of the iron and steel plants. Thus, in order to increase the productivity of the EAF, the following is required: to increase the speed of melting, to optimize the balance of carbon and oxygen supplied to the furnace and to minimize energy consumption. For the latter, thermal losses must be reduced and the temperature profile during melting must be controlled [9].

The research is aimed at obtaining the relationships directly linked in the fusion process, and then by the technique of modeling structural equations determine which are the critical variables involved in the process. The validation of the mathematical model was carried out in a steel production plant, with a range of 1360 castings.

The industrial data from this investigation were collected at the aforementioned plant, located in the center of Ecuador. The raw material used in the manufacture of steel is recycled metal scrap, mostly dismantled ships. Other sources of processed iron ore are cast iron (HBI) and reduced iron (DRI) briquettes. Recycled metal scrap contains 35-56% iron, and HBI and DRI briquettes have an iron concentration of 75-85%.

The model was validated in an electric arc furnace (EAF) of 50 tons of uncoated capacity; the steel is emptied eccentric type by the bottom (EBT), cast; the feeding of scrap is done with a continuous feeding system called CONSTEEL, which uses moving tables in order to move the metal scrap from the loading area to the entrance to the EAF furnace.

Melting scrap metal using an EAF type furnace has become one of the main methods of steel production worldwide [10]. The main objective of this equipment is

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to perform its function in the shortest possible time; an opportunity to reduce even one minute of this process is very important [11]. This study will provide knowledge on the interaction of metallurgical variables, for an adequate decision making related to productivity.

A. Method of Structural Equations (SEM)

The estimation of a model of structural equations begins with the formulation of the theory that supports it. This theory must be formulated in such a way that it can be tested with real data. Specifically, it must contain the variables that are considered important to measure. The theoretical model should specify the relationships expected to be found between the variables (correlations, direct effects, indirect effects, loops). It is normal to formulate the model in graphical form (causal or structural diagrams); from there it is easy to identify equations and parameters [12].

The structural equation model (SEM) is a technique that combines both multiple regression and factor analysis. The structural model is the guiding model, which relates independent variables and dependent variables [13].

B. Determination of critical variables

According to Escobedo [14], structural equation models establish the relationship of dependence between variables. He tries to integrate a series of linear equations and establish which of them are dependent or independent of others, since within the same model the variables that can be independent in one relationship can be dependent in others, so that the technique of structural equation modeling (SEM) becomes a useful tool.

The following are the observable and latent variables involved in the steel melting process for this study. These variables are the result of daily work experience:

Observable variables, represented graphically by squares or rectangles [15]:

E: Energy consumption for melting by casting

C_{ppl}: Specific heat of the liquid foot

P: Average electrical power used

M: Scrap loading, considering its metallic efficiency on the basis of the emptied liquid steel

F: Consumption of fluxes

A: Anthracite consumption

O: Oxygen consumption

P_{on}: Power On, is the time it takes the laundry connected the EAF

P_{off}: Power Off, is the time it takes to melting, disconnected the EAG

X_1: Tons of liquid steel emptied

Latent variables, represented graphically by circles or ovals [15]:

E_{ch}: Specific energy consumption for melting one tonne of scrap metal

E_f: Specific energy consumption for melting one tonne of fluxes

E_a: Specific energy consumption for melting one tonne of anthracite

E_q: Chemical energy generated by the exothermic formation reaction of CO

E_{pl}: Specific energy consumption for heating the liquid foot

M_{pl}: Liquid foot mass

ΔT: Temperature variation from melting to heating

C: Number of melting produced per day

C_e: Cost of electrical energy

C_m: Raw material cost

C_t: Cost of transformation without cost for consumption of electrical energy

H: Hourly availability, considering only the effective production hours

TTT, Tap to Tap: sum of connected time, power on, plus disconnected time, power off

Y_1: Productivity

Y_2: Cost

II. RESULT AND DISCUSSION

Using the technique of linear regression to the proposed observable and latent variables, the model of structural equations (SEM) was defined with the criterion of accepting those items whose significance is greater than or equal to 0.5 [14], obtained from a historical database of the steel mill, remaining compounds as shown in Fig.1.

Energy consumption (E) is the most significant observable variable for productivity with a value of 0.878, the mathematical model that defines this variable is a function of the weight charge and the number of tons of steel emptied according to (1)

$$E = (E_{ch} * X_1 * M) + \left(E_{f*}F\right) + (E_a * A) + E_{pl} - E_{q.} \quad (1)$$

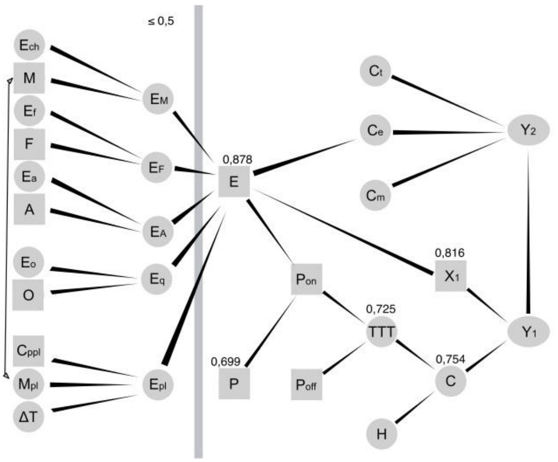


Figure 1. Significance of the observable and latent variables of the model of the steel melting process

In Fig. 2 shows the total energy consumption per casting (E), broken down into its components, which are shown below.

Chemical Energy Consumption (E_q) is calculated with (2) which relates the chemical energy of oxygen (E_o) and its mass flow (O)

$$E_q = E_o * O. \quad (2)$$

Additionally electrical energy consumption required to keep the steel liquid foot melted inside the EAF (E_{pl});

determined by (3) relating the mass of the liquid foot (m_{pl}), the specific heat of the steel (C_{ppl}) and the required temperature increase (ΔT)

$$E_{pl} = m_{pl} * C_{ppl} * \Delta T. \quad (3)$$

The consumption of electrical energy necessary for the fusion of a casting (E_M); it is determined with (4) that relates the electrical energy necessary to melt a ton of metallic scrap (E_{ch}) and the tons of metallic scrap fed (M)

$$E_M = E_{ch} * M. \quad (4)$$

In addition, the consumption of electrical energy used to melt one ton of fluxes (E_F) is determined by (5) which relates the electrical energy needed to melt one ton of fluxes (E_f) and the tons of fluxes fed (F)

$$E_F = E_f * F. \quad (5)$$

Also the consumption of electrical energy required to melt one ton of anthracite (E_A) is determined by (6) which relates the electrical energy needed to melt one ton of anthracite (E_a) and the tons of anthracite fed (A)

$$E_A = E_a * A. \quad (6)$$

In Fig. 3 and (7) it is observed how the tons of liquid steel emptied (X_1) and the number of castings produced per day (C) influence productivity (Y_1)

$$Y_1 = C * X_1. \quad (7)$$

Thus the number of casts produced per day results from the relationship between hourly availability (H) and tap to tap (TTT), as shown in (8)

$$C = \frac{H}{TTT}. \quad (8)$$

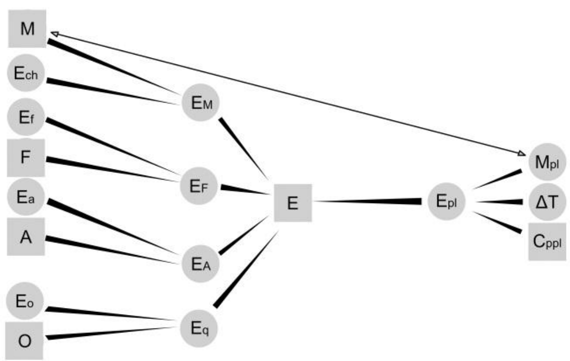


Figure 2. Total energy consumption (MWh) per casting in an EAF

The total tap to tap time is described by (9) as the sum of the time the furnace remains on (P_{on}) and the time the furnace remains off (P_{off})

$$TTT = P_{on} + P_{off}. \quad (9)$$

Thus, power on (P_{on}) results from the relationship between total energy consumption and the average electrical power supplied by the transformer, according to (10)

$$P_{on} = \frac{E}{P}. \quad (10)$$

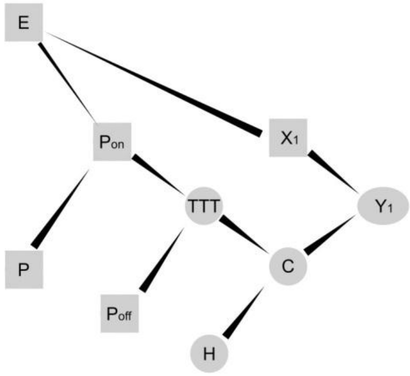


Figure 3. Productivity (Mg) per day in an EAF

Finally, the production cost (Y_2), shown in Figure 4, considers the sum of the cost of electricity consumption (C_e), the cost of raw material (C_m) and the cost of transformation (C_t), as shown in (11)

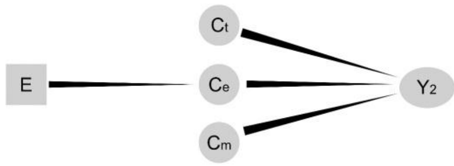


Figure 4. Total cost (USD) per tonne of steel produced

$$Y_2 = \frac{\left((E*C_e)+\left((C_m+C_t)*X_1\right)\right)}{X_1}. \quad (11)$$

So as a result of the research, the objective function of the melting process according to the interactions analysed is productivity (Y_1), which is proportional to the number of castings produced per day (C) and to the tons of steel emptied (X_1) (7).

Considering that the most significant variable is energy consumption (E), it is identified that the critical manipulable variables of the process are the steel tap temperature (2) and the scrap metal load (1).

Once the critical variables have been determined, the proposed model is validated, considering a quadratic mean approximation error (RMSEA) less than or equal to 0.05 as an acceptable fit level [14], Table 1.

TABLE I. VALIDATION OF THE PROPOSED MODEL

N° Melting	Avg Tap Temp	Avg Charge Weight	Production		RMSEA
			Experiment	Estimated	
320	1611	35.22	92215	92210	0,03
476	1610	36.96	150263	150270	0,05
564	1602	36.22	115535	115530	0,01

The proposed fusion model was validated with 1360 controlled tests in the steel production plant. The tap temperature was evaluated in the range of 1615 to

1660 ℃, while the scrap metal load was evaluated in the range of 35 to 39 Mg.

In Fig. 5 and 6 the validity of the relationships proposed in the model for steel melting are verified experimentally, the information was obtained from the historical database of the production process.

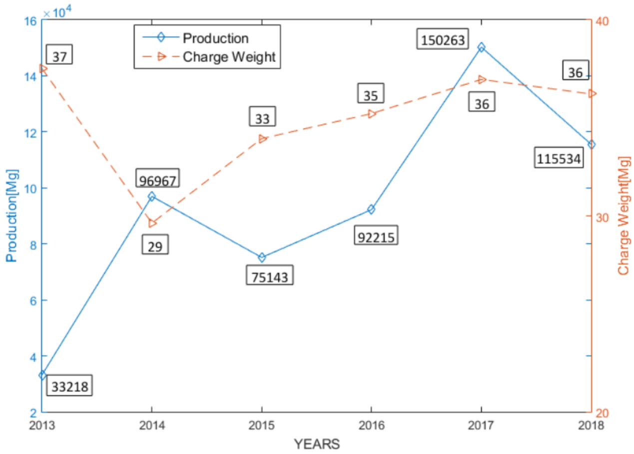


Figure 5. Increased productivity in relation to the scrap metal load fed to the EAF

The results show that an increase in the load of metal scrap fed to the furnace favours productivity. Having a higher scrap load implies a longer total emptying time if the power of the transformer remains constant (3), therefore, it is also important to consider the flexibility of the electrical programs for steel melting and to guarantee the stability of the electric arc in the three phases through an adequate regulation of the electrodes and homogeneity in the density of the scrap load.

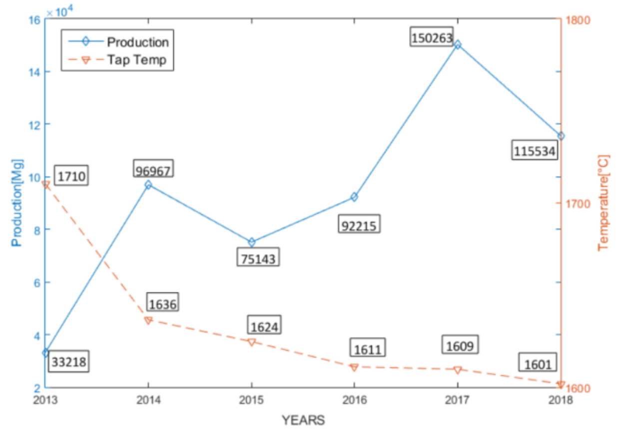


Figure 6. Increase in productivity in relation to the decrease in the casting temperature of the EAF

As the tap temperature decreases, the energy supplied to keep the steel foot in liquid phase inside the furnace also decreases (2), therefore the time the furnace remains connected is also shorter (3), which leads to a decrease in the total casting time (4) and therefore the total number of castings per day is greater (5), which is directly related to the increase in productivity (6).

The benefits of lowering the tap temperature are not only reflected in productivity, the useful life of the refractory lining the furnace also increases, the maintenance of the cooling system decreases, the requirement for chemical energy through the combustion reactions of anthracite decreases, ie the environmental impact per generation of combustion gases is also lower.

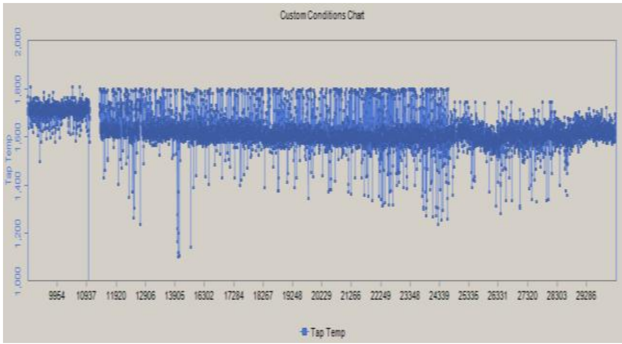
III. Conclusion

The model obtained demonstrates the relationship between the variables and the constructs under study, productivity being directly proportional to the load of metal scrap fed and inverse to the tap temperature. The increase in the number of casting due to the decrease in the tap to tap increases productivity.

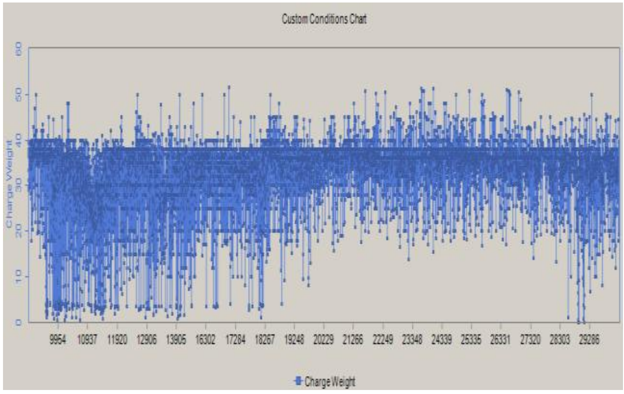
The method of structural equations SEM allowed to identify accurately the interactions of operational parameters, metallurgical variables, restrictions referring to the installed capacity of the equipment and operational availability. The model is of great benefit to the company since it facilitates decision making in order to improve productivity, and this methodology can be applied in other areas.

The model is consistent with the experimental results obtained in the production plant; however the critical variables, emptying temperature and metal scrap loading, could be subject to an optimization study, in order to maximize productivity and minimize the production cost.

Appendix A Historical Casting Temperature Database 2013-2018



Appendix B Metal Scrap Loading History Database 2013-2018



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REFERENCES

[1] M. Martinez, and A. Ramirez, "Simulation of mathematical models for the steel refining process in the pot furnace," *Engineering thesis, School of Chemical Engineering and Extractive Industries*, National Polytechnic Institute, México, 2012.

[2] A. Huang, Y. Wang, H. Gu, and Y. Zou, "Dynamic interaction of refractory and molten steel: Effect of aluminamagnesia castables on alloy steel cleanness," *Ceramics International*, 2018.

[3] A. Gonzalez, L. Paoli, and J. M. Cullen, "How resource-efficient is the global steel industry?" *Resources, Conservation & Recycling*, vol. 133, pp. 132-145, 2018.

[4] A. Babich, D. Senk, "The Coal Handbook: Towards Cleaner Production," *Woodhead Publishing Series in Energy*, vol. 2, 2013, ch 12, pp. 267-311.

[5] K. Sheth. (April 2017). All About The Steel Industry. *Worldatlas.* [Online]. Available at: https://www.worldatlas.com/articles/all-about-the-steel-industry.html. Accessed on: 16 September 2018.

[6] C. Gálvez, "Empirical model design for industrial processes: stainless steel refining," Ph.D. dissertation, Dept. Electron., Málaga Univ., Málaga, 2007.

[7] B. A. Pereira, J. A. De Castro, A. J. Da Silva, and J. A. R. Durán, "Modeling of the conventional process of continuous Interstitial Free casting," *Information Technology*, vol. 21, no. 6, pp. 3-12, 2010.

[8] J. Barco, J. Palacios, C. Ojeda, and M. Ojanguren, "Global modelling of continuous casting process," *Metallurgy Magazine*, vol. 41, no. extra, pp. 463-468, 2005.

[9] E. E. Navas, J. Arzola, L. García, "Systemic analysis of the task of dosage of batches in HAE under use of manganese mineral conditions," *Mechanical Engineering*, vol. 1, pp. 15-24, 2008.

[10] L. Piqueras, J. L. López, L. Martínez, A. Marcos, "Sulfur content modelling for liquid steel in the electric arc furnace," *in Proc. of the 17th International Congress on Project Management and Engineering*, July 17-19th, Logroño, 1358-1366, 2013.

[11] M. Blachnik, K. Maczka, and T. Wieczorek, "A Model for Temperature Prediction of Melted Steel in the Electric Arc Furnace (EAF)," *in Proc. of the 10th International Conference, ICAISC 2010, Part II*, June 13-17, Zakopane, Poland, 371-378, 2010.

[12] M. A. Ruiz, A. Pardo, and R. San Martín, "Structural equation models," *Psychologist Papers*, vol. 31, no. 1, pp. 34-45, 2010.

[13] M. Cupani, "Analysis of structural equations: Concepts, development stages and an application example," *Thesis Magazine*, vol. 2, no. 1, pp. 186-199, 2012.

[14] M. T. Escobedo, J. A. Hernández, V. Estebané, G. Martínez, "Structural equation modeling: features, phases, construction, implementation and results," *Ciencia & trabajo*, vol. 18, no. 55, pp. 16-22, 2016.

[15] M. E. Gomez, "Estimation of the models of structural equations, of the Mexican index of satisfaction of the user of Mexican social programs, with the methodology of partial least squares," Engineering thesis, University Iberoamericana, México, 2011.

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