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Scrap production of extruded aluminum alloys by direct extrusion

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Abstract

The growing globalization of the different types of market requires that companies invest, in a recurrent way, to optimize and improve all the processes inherent to their activities. Aluminium extrusion is the main industrial process used to create profiles of a fixed cross-section. This process requires appropriate processing parameters to be used, in order to produce diverse profiles and high-quality products. The company's ability to adapt and improve the productive process are differentiating factors against the competition. Thus, understand the main operations and dynamics of the companies is crucial. This work presents an empirical study concerning the extrusion process of a Portuguese company in the aluminium sector. By analysing a real data base provided by the company, the main objective is to model the aluminium extrusion process. Taking into account the variables that most influence the extrusion of different profiles, the aim is to minimize the production of scrap. First, by studying the literature in the subject, the variables that most contribute to scrap production were identified. Since the database provided by the company did not present all the variables described in literature, proxy variables were considered. Next, a multivariate linear regression model for explaining the amount of scrap taking as explanatory the identified variables was estimated. With this analysis, it was possible to identify levels of significance of the variables under study, and therefore understand how each of the variables contributes to the increase or decrease of the amount of scrap on the production of aluminium profiles. The results show that variables concerning with extrusion temperature, time, speed, pressure and die geometry are crucial to improve and control the scrap production. The obtained model will be improved, in future work, by including further variables of the extrusion process. Furthermore, factor analysis and GHML methodologies will also be considered for explaining the production of scrap and therefore improve the production process.

Keywords: Aluminium Extrusion; Scrap; Extrusion Variables; Multivariate Linear Regression.

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1. Introduction

Since the 19th century, extrusion technology allows the production of a variety of geometry components [1-3]. During the World War II, the use of the extrusion technique was intense, since different profiles of extruded aluminium were used for the manufacture of aeronautical components [4]. Nowadays, a large number of different types of extruded aluminium profiles are found in the most diverse industrial areas and markets, such as, construction, transport, motor sports, industry and structures. An increasingly demanding industry promotes the dynamic between high quality and low price, without loss of product specifications, leading to new industrial challenges. As recognized by Moreira [5], due to the market demands and customer requirements, product conformity and quality are indissociable. In fact, these concepts together make the product a value-added creation.

In the metallurgical industry, extrusion is a first-line technique [2]. Extrusion offers unique construction and design possibilities, with different functional characteristics [2,6]. It is a process with endless opportunities, as it allows to obtain long extruded profiles, with several cross-section formats. Extrusion is an extremely complex process influenced with several variables. These variables come from numerous sources and in the various phases of the process (pre-extrusion, extrusion, post-extrusion), and must be controlled to ensure the specificities of both the product and the customer, as well as the maximum scrap reduction [5,7].

The quality of any extruded product is a function of various factors, such as geometrical dimensions, chemical composition, appearance and regularity of the microstructure, variation of mechanical properties (over the extruded length and cross section), and surface finish. In the process, the contamination of the billet-to-billet interface by oxides, dust, or lubricant, produces a welded zone with reduced mechanical properties, that requires profile discharge. Additionally, less or inadequate control of the extrusion variables may result in the appearance of defects or poor mechanical properties. The defective billets; defective or inadequate tools; defects arising during extrusion; and resulting failures in the course of post-extrusion operations, are considered the main sources of defects and product rejection [3, 8, 9]. At the several positions of the longitudinal welds, transverse welds and back-end defects, the strain concentration phenomena occur [10,11]. Yet, the behavior of the metal flow may form a macro bore in the extruded profile [10]. Under certain combination of extrusion ratio, die angle, height of the deformation zone, friction and material behaviour, the extruded product or the extrudate may develop defects, such as axial hole or funnel, fir tree cracking, pipe or fish tail, centre burst or chevron cracking [12]. Carvalho [13] identified die lines, blister, crack and weld lines as surface defects which led to increased production costs, delays in delivery and upsurge of the scrap.

In turn, it is necessary to understand the contributing and controlling factors related to the defects of the product in the extrusion. Qamar, Pervez and Chekotu [3], identified die corrections using a frequency-based statistical study of the die defects. Chang, Shih and Tzou [14], showed a significant improvement in actual mass production, and die's service life, applying the simulation software Deform 3D and the Taguchi Method Orthogonal Array L9 (34) statistic method. Its research includes the choice of die materials, angle of compression fit and inner and outer ring shrink fit, to choose the optimal combination as an effective basis to improve the die life. To investigate the effect of a variety of parameters numerical analysis, a commercial finite element analysis software (FEA) MSC.Marc2007r1, was used [12]. That allowed to achieve a physical modeling experiments to validate FEA results. To other hand, using the finite element method (FEM) the profiles temperature was predicted [15]. It is observed that with the increase of the deformation temperature or decrease of the rate of deformation, the average size of recrystallized grain increases. The formation of coarse grains at the periphery of the extrudate is attributed to high temperatures raised during extrusion rather than high deformation rates. Jie *et al.* [16], in order to solve the defects of the inferior concave appearing in the extrusion experiments of complex hollow aluminum profiles, uses a 3D finite element model based on HyperXtrude software by means of Arbitrary Lagrangian–Eulerian (ALE) algorithm. In this work, the die structure was optimized by the addition of deflecting plates. The research method provides an effective orientation to improve extrusion defects and optimize the metal flow. The behaviour of the material flow studied, and the formation of back-end defects and transverse welds, has been revealed through a numerical probe [10,11].

In the present work, the possible causes of the high quantities of scrap generated in the production of the aluminium profiles during the extrusion process, will be studied by estimating multivariate linear regression models adjusted to a set of pre-collected data from a Portuguese company in the aluminium extrusion sector. The indicators obtained in this analysis will allow the evaluation of the main variables that contribute to the production of large quantities of scrap.

Therefore, it will be possible to adopt corrective measures by adjusting the variables in the extrusion process and thus minimize the quantity of scrap and optimize the extrusion process.

The rest of this paper is organized as follows. In Section 2, a brief literature review on the aluminium extrusion process and the description of the methodology used in this research, are presented. Section 3 presents the empirical study that will be discussed in order to answer an industrial problem from the extrusion process of a Portuguese company that aims at reducing the amount of generated scrap generated. This Section also presents the real database that will be used for the proposed multivariate model, as well as the models validation and discussion. This paper concludes with a summary of the findings and suggestions for future work in Section 4.

2. Literature Review

2.1. Aluminium Extrusion

The extrusion is a technological process of plastic deformation, where the material subject to high pressures is forced to pass through the holes of a die (matrix) [2]. This technique is used to transform an ingot into a useful product, with the required size and shape required. Generally, there are two types of extrusion: direct extrusion and indirect extrusion [1,2]. In the direct extrusion process, the die is fixed, and the stem forces the metal through the die holes. In the indirect extrusion process, the die is contained within the hollow rod, which moves toward the fixed billet, forcing the heated metal to flow into the rod. Besides this difference, the pressure is the main difference between the two types [1]. Extrusion pressure for direct extrusion is lower than that for indirect extrusion. Thus, direct extrusion is the process required for produce long profiles [2], for that it is the type of process considered in this study. The extrusion technology allows manufacturing very varied geometry components [8] making use of a wide range of metallic materials of which stand out aluminium alloys [2].

Aluminium (Al) is a metal obtained from the ore called bauxite and if has been at the service of the industry for more than 150 years, providing excellent mechanical properties. Besides, the aluminium is an electric conductive and thermal, acoustic insulation, lightweight and anticorrosive material [4] that industrially identifies this metal, in form of alloys (example AlMgSi) as a metal for mechanical work [17]. Over time, aluminium alloys produced have been extensively studied and developed. For Arif [8], the quality of any extruded product is influenced by the chemical composition of the alloy, which affected greatly the way in which the metal flows during extrusion. For Ikumapayi [18], the temperature in the deforming billet is redistributed throughout the extrusion process from the transient state to the steady-state. However, the extrusion can become impossible or can yield an unsatisfactory product. The two main reasons that may contribute to these results are: i) the required load exceeds the capacity of the press available; or, ii) the temperature of the extrusion exceeds the solidus temperature of the alloy. According to Saha [2], the critical variables that influence the force required for extrusion and the quality of material are extrusion ratio (E.R.), working temperature (T_B); speed of deformation (V_R); and alloy flow stress ($\bar{\sigma}$) (Fig. 1).

In the optimization of extrusion, speed and temperature, are considered the key variables to maximize productivity [2]. For a specific billet size, extrusion ratio, and the type of die, is necessary firstly to optimize the billet temperature, before increasing the extrusion speed. The purpose of determining the optimum billet temperature is to reduce the acceleration time, without compromising the maximum extrusion speed (Fig. 2).

The investigation by Tibbetts [19] focuses on surface quality and micro-structural uniformity of the product. The model presented directly relates the mathematical description and the physical phenomena, where the parameters and control variables enter into the model equations, so that the identification and open-loop optimization problems are tractable. Alta and Kobayashi [20], used numerical methods to predict the local temperature, extended to calculate the non-steady-state temperature distribution in extrusion process. They concluded that the approaches developed would have to be improved, by considering the tool-material interface and the analysis of extrusions with higher extrusion rates.

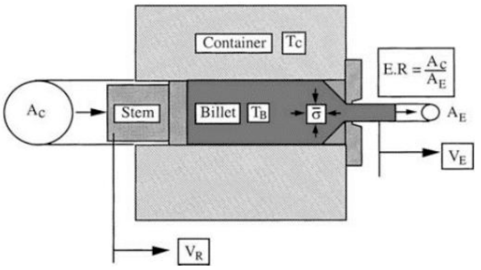


Fig. 1 - Extrusion variables [2].

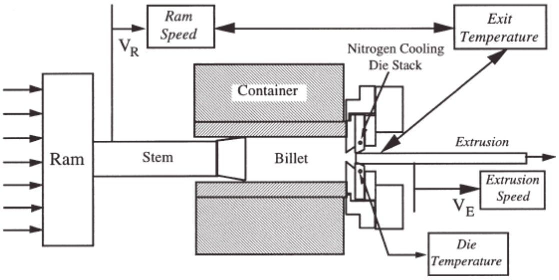


Fig. 2 - Temperature and speed control extrusion [2].

Reiso [21] discusses the effect of some key factors in the aluminium industry that determine productivity and product properties during extrusion of AlMgSi alloy. According to the author, at highest extrusion speeds, the mechanical properties and surface quality were significantly improved with billet preheating practices. Although, the complex extrusion process must be considered as a whole, since what happens in one step, it is not independent of the others, in the process chain. Like any other metal-forming process, it is intended to extrude aluminium at a maximum production rate and a minimum production scrap rate. Reducing scrap to the minimum is always the goal to be achieved [21,22]. In the course of the present study we have the opportunity to analyse some of the variables referenced by this author. Thus, some research hypotheses have been formulated in the next section, related to billet temperature (T_B), extrusion time (t_E), RAM speed (S_{RAM}), container pressure (p_C) and extrusion ratio (E.R.).

2.2. Research Hypotheses

To achieve the proposed objective, and based in literature study, five research hypotheses that relates the amount (kg) of scrap produced in the production of each billet (as dependent variable) with the various (independent) variables, were formulated. The software IBM SPSS Statistics 25 was used to test the hypotheses that are presented next.

2.2.1. Billet Temperature

Extrusion of aluminium alloy is recommended to operate at billet temperatures of 420-430ºC [23]. Operating above these temperatures would cause profile defects, thus leading to scrap. Li [24] evaluated the temperature evolution in the extrusion process, by mean of a computer simulation (3D FEM) and found that extrusion is limited by two factors: temperature and pressure. Furthermore, temperature is one of the most important parameters in extrusion [25], since the flow stress is reduced if the temperature is increased and deformation is easier.

During the extrusion process, many of the deformation rate depends on the: i) billet temperature, ii) heat transfers from the billet to the container, and iii) heat developed by deformation and friction. These thermal changes start as soon as the hot billet is loaded into the usually preheated container, and extrusion is started [2]. Also, in the billet-on-billet extrusion the perfect welding of the previous billet with the following billet must occur when the joint passes through the deformation zone [24,26]. Regarding product quality, outlet temperature affects heat treatment process, dimensional stability and causes extrusion defects [2]. The extrusion variables directly influence the outlet temperature. For e.g., the temperature developed in extrusion increased with the increasing of the ram speed [2,24]. Regarding the discussion, the first research hypothesis is defined as follows:

H1: The amount of scrap is higher when the extrusion temperature is lower.

2.2.2. Extrusion Time

During the extrusion process, it is necessary to ensure not only the temperature, but also the extrusion time, since both are necessary for the complete solubilisation [27]. On the other hand, acceleration time can be reduced by improving the extrudability of the alloy and by making compositional adjustments of the raw-material or using an optimal homogenization process [28].

As the inadequate extrusion conditions can lead to products with undesirable defects and mechanical properties, it is important to know how to reduce acceleration time. This time also helps to reduce the total extrusion cycle time and to increase productivity [2]. In literature [2,7] different ways to reduce the cycle time, for each alloy and billet size are presented by taking: i) increasing the ram speed for the fixed billet temperature; ii) reducing the extrusion ratio by increasing the number of holes in the die; or, iii) adjusting the initial billet temperature for the fixed ram speed. Regarding the discussion, the second research hypothesis is defined as follows:

H2: The amount of scrap is lower when the extrusion time is shorter.

2.2.3. Ram Speed

The response of metal to extrusion processes can be influenced by the speed of deformation. For each alloy, as referred before, some parameters must be adjusted [29]. It is consensual to consider that increasing the extrusion speed causes increased extrusion temperatures [2,30]. This increase is due to the fact that the strain rate is directly proportional to the ram speed, so that the magnitude of the generated heat is proportional to the strain rate. Contrary, the lower the ram speed, the time available for the generated heat flux increases and heat conduction is also more pronounced. In the case study by Ikumapayi [18], the ram speed affects the amount of heat generation and also the amount of heat loss to the extrusion tooling, and thus has a major influence on the temperature values, in the remaining billet and temperature distributions. Regarding the discussion, the third research hypothesis is defined as follows:

H3: The lower extrusion speed influences the amount of scrap in the extrusion process.

2.2.4. Pressure (container)

Current research on extrusion has recognized that higher extrusion ratios require higher extrusion pressure [8]. Robbins [31] considered that the unit pressure required for extrusion is the primary consideration in the selection of an extrusion press. According to Li [24], the process is essentially limited by the load capacity of the press. The specific pressure for a certain diameter of the container should be greater than the pressure required to push the billet preheated through the die, otherwise the extrusion fails [2].

During the extrusion process, the normal pressure on the bearing surface of the die is very high. This pressure is assumed equal to the extrusion pressure, which is equal or higher to the flow stress of the material. The extrusion pressure is influenced by extrusion variables, such as ram speed, which increases with its increase, the geometries of the billet, the die, as well as the container and stem [18]. Regarding the discussion, the fourth research hypothesis is defined as follows:

H4: The amount of scrap is greater the lower the pressure.

2.2.5. Extrusion Ratio

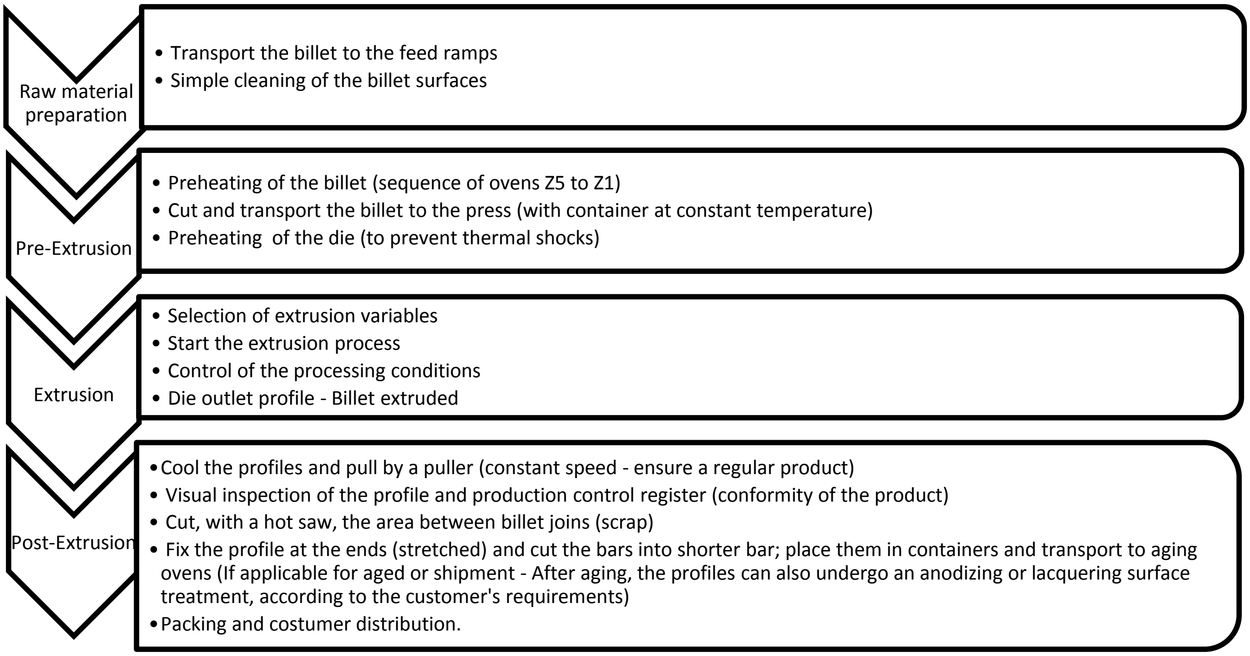
Bajimaya [32], in line with the vision of Saha [2], concluded that the metal flow is influenced by several factors, such as: temperature of the billet and the container, extrusion pressure, extrusion speed, billet size and also extrusion ratio (ER). Using finite element models, the authors found that the models provide the information needed for theoretical analysis but cannot be applied directly to the manufacturing execution system, because the results are not realistic enough. Later Peris [33] have found that the temperature rise is ruled by the E.R., maintaining constant billet temperature and ram speed. Such behaviour results from material deformation due the friction at the die. Otherwise, both extrusion speed and acceleration time increases, with an increase of E.R. A greater slope on the acceleration curve was observed, with the decrease of the E.R. [2]. Regarding the discussion, the fifth research hypothesis is defined as follows:

H5: The amount of scrap is higher with the increase in extrusion rate.

3. Empirical Study

3.1. Company and its problematic

The company under study is dedicated and specialized in the development and production of aluminium profiles, it was founded in 2011 and its core-business is aluminium production [34]. The company has the facilities equipped with a 2500 Ton press, the production capacity of 800 Ton/month allowing to produce profiles with 320 mm x 20 mm and weighing up to 25 kg/m. The company has developed several control systems for quality, in particular, the three-dimensional analysis of aluminium profiles, which allows checking for occlusions that the parts may present. De Almeida [35] described the company extrusion process from the delivery phase of the raw material, until the distribution phase for customers. The aluminium billets arrive at the company and are checked, confirming the raw material quality certificates. According to the specification and the costumers, the production planning is carried out. The production system starts the extrusion process of the profiles taking into account the summarized steps presented in Fig. 3.



- Transport the billet to the feed ramps
- Simple cleaning of the billet surfaces

- Preheating of the billet (sequence of ovens Z5 to Z1)
- Cut and transport the billet to the press (with container at constant temperature)
- Preheating of the die (to prevent thermal shocks)

- Selection of extrusion variables
- Start the extrusion process
- Control of the processing conditions
- Die outlet profile - Billet extruded

- Cool the profiles and pull by a puller (constant speed - ensure a regular product)
- Visual inspection of the profile and production control register (conformity of the product)
- Cut, with a hot saw, the area between billet joins (scrap)
- Fix the profile at the ends (stretched) and cut the bars into shorter bar; place them in containers and transport to aging ovens (If applicable for aged or shipment - After aging, the profiles can also undergo an anodizing or lacquering surface treatment, according to the customer's requirements)
- Packing and costumer distribution.

Fig. 3 - The company extrusion process [28].

The methodology followed in the next sections is developed to answer to the company's problem, i.e.: How to minimize the amount of scrap generated in the continuous production in order to improve the process, and subsequently, guaranteeing the quality and seeking its sustainability.

3.2. Database

After the study by Carvalho [13], carried out with a small amount of available data, the company understood the importance of data collection and analysis for the improvement of the process, and decided to purchase a software to record the production data. In order to perform the present empirical study, the company provided a database with information on the continuous aluminium production of various profiles, referring to the first semester of the year 2018. Thus, from the data provided, a refining was done, grouping the totality of the data in a single database, so that the information in the study can be as relevant as possible for the analysis. Analyzing the sample, the database includes

42 827 observations, corresponding each to an extruded billet. The database contains 65 variables, 62 of which are quantitative (discrete and continuous) and three are qualitative (nominals). Depending on the phase of the process, these variables can be divided into three categories: pre-extrusion, extrusion and post-extrusion. In this work we consider only the extrusion phase variables (See Table 1 for the list of variables and corresponding acronyms). The variables $\mathrm{PR\_W_B}$ (Weight Billet, kg) and $\mathrm{PO\_W_B}$ (Bars Weight, kg), define the quantity of scrap, SC_{KG},

$$\mathrm{SC_{KG}} = \mathrm{PR\_W_B} - \mathrm{PO\_W_B}. \tag{1}$$

The selection of the variable $\mathrm{SC_{KG}}$ and the other available variables is related to the objectives of the work, i.e. the deeper understanding of the contextual factors that are associated to the production of scrap. On average there are 11.16 kg of scrap in the extrusion of each billet, with a minimum of 0.76 kg and a maximum of 92.79 kg of scrap. Of the 42827 billets extruded, 50% produced 8.47 kg of scrap or less, and 50% produced this value or more. The standard deviation of scrap is 9.28 kg. Therefore, the amount of scrap is considerable and must be minimized, in order to improve the overall equipment efficiency.

Regarding the recorded values, it can be observed that 50% of the times in the extrusion process dies with 2 holes or less are used, the average of the specific weight of each billet is 1.55 kg/m and the maximum billet length is 1113.00 mm. The pressure has values between 246.79 bar and 282.00 bar and the maximum pressure presents values between 435.43 bar and 451.00 bar. As far as the time variables are concerned, the average of the extrusion time is 173.93 s, the maximum speed time is 452.00 s and the dead time is at least 12.00 s.

3.3. Model for the Aluminium Alloy Profiles Scrap

With a multivariate linear regression, the objective is to determine the variables that influence the production of scrap – dependent variable ($\mathrm{SC_{KG}}$), in 42 827 billets. The choice of independent variables to be considered in the analysis was performed from the set of variables included in the company's database and according with the literature review. However, in this work, only the extrusion phase is considered. The independent variables identified in literature and the ones existent in the database and considered in the model here presented are depicted in Table 1.

Table 1 - Variables consider in the linear regression model

Literature review	Variables considered
Billet Temperature	$\mathrm{E\_T_{C,P}}$: Extrusion Post Container Temp (ºC); $\mathrm{E\_T_{End}}$: Extrusion End Temperature (ºC);
Extrusion Time	$\mathrm{E\_t_D}$: Extrusion Dead time (s); E_t: Extrusion time (s);
Ram Speed	$\mathrm{E\_t_S}$: Extrusion Speed Time (s); $\mathrm{E\_S_C}$: Extrusion Speed (mm/s);
Pressure (container)	$\mathrm{E\_p_{SL}}$: Extrusion Sealing Pressure (bar); $\mathrm{E\_p_{Max}}$: Extrusion Pressure Max (bar);
Extrusion Ratio	$\mathrm{E\_L_B}$: Extrusion Billet Length (mm); $\mathrm{E\_L_{Butt}}$: Extrusion Length Butt (mm); E_NH: Extrusion Number of Holes; E_SW: Extrusion Specific Weight;

The stepwise method was used to estimate the model. This method considers all significant variables, for a 5% significance level. The model has an adjusted R square of approximately 46%, this is the expected percentage of total variability in scrap production explained by the independent variables included in the linear regression model. The coefficients of the final model are in Table 2. This table also shows the standardized coefficients. All variables are significant to explain the production of scrap in the extrusion process of each billet. Some variables show more importance in the model than others. The analysis of the standardized regression coefficients shows that the variables $\mathrm{E\_t_D}$, E_SW, E_t, E_NH and $\mathrm{E\_p_{Max}}$ are those that have the greatest relative contribution to explain the dependent variable, i. e. the amount of scrap, $\mathrm{SC_{kg}}$.

The model expressed in equation (2) translates the concepts previously referred in literature, since the variables that are most associated to the production of scrap during the aluminium extrusion process are those identified.

By analyzing the coefficient of the variables $\mathrm{E\_T_{C,P}}$ and $\mathrm{E\_T_{End}}$ there is statistical evidence to validate **H1.** Also, it is possible to infer that there the corresponding negative coefficients, confirming that scrap is higher when extrusion temperature is lower. **H2** is also validated by the coefficients of the variables $\mathrm{E\_t_D}$ and E_t, which are the most important in the model and contributing positive for the amount of scrap produced. The speed and the various factors associated with it validates **H3**, positively by the variable E_t_S and negatively by the variable E_S. With the analysis of the coefficient of the variables E_p_{SL} and E_p_{Max} it is possible to see statistical evidence confirming **H4**, and the amount of scrap greater the lower is E_p_{Max} and inversely is greater the upper the E_p_{SL}. The extrusion ratio, having into account the coefficient of the variables, E_L_B, E_L_{Butt}, E_NH and E_SW, is relevant, been the amount of scrap higher with their increase, confirming **H5**.

Table 2 – Coefficients and collinearity diagnosis

Model		**Unstandardized Coef.**		**Standardized Coef.**	**t**	**Sig.**	**Collinearity Statistics**	
		B	Std. Error	Beta			Tolerance	VIF
12	(Constant)	57.54	8.50		6.77	0.00		
	E_t_D	1.31	0.01	0.51	131.67	0.00	0.84	1.19
	E_SW	1.47	0.02	0.31	61.05	0.00	0.49	2.05
	E_t	0.04	0.00	0.19	30.20	0.00	0.32	3.15
	E_NH	0.67	0.02	0.12	28.06	0.00	0.70	1.43
	$E\_T_{C,P}$	-0.21	0.01	-0.09	-23.35	0.00	0.83	1.21
	E_p_{Max}	-0.06	0.00	-0.12	-22.58	0.00	0.47	2.15
	E_L_{Butt}	0.12	0.01	0.06	15.61	0.00	0.89	1.12
	E_L_B	0.01	0.00	0.06	13.12	0.00	0.53	1.87
	E_t_S	0.01	0.00	0.03	6.37	0.00	0.79	1.26
	E_S	-0.24	0.04	-0.04	-5.67	0.00	0.32	3.14
	E_T_{End}	-0.01	0.00	-0.02	-5.20	0.00	0.86	1.17
	E_p_{SL}	0.08	0.03	0.01	2.64	0.01	0.99	1.01

a. Dependent Variable: $\mathbf{SC_{KG}}$ “Scrap (Kg)”

The model can be written as:

$$\begin{aligned} SC_{KG} &= 57.54 + 1.31E\_t_D + 1.47E\_SW + 0.04E\_t + 0.67E\_NH - 0.21E\_T_{C,P} - 0.06E\_p_{Max} + 0.12E\_L_{Butt} \\ &\quad + 0.01E\_L_B + 0.01E\_t_S - 0.24E\_S - 0.01E\_T_{End} + 0.08E\_p_{SL} \end{aligned} \tag{2}$$

Linear regression approach assumes that residuals are independent and identical distributed, with a zero mean normal distribution and constant variance. When samples are large, the Kolmorogov-Smirnov (K-S) or Shapiro-Wilk (SW) normality tests leads to the rejection of the residuals’ normality. In this case, the central limit theorem which indicates that the larger the sample size, the closer to a normal distribution the distribution of the means can be used. In practice, if the study sample has more than 30 cases, which is the case, the distribution of the means can be satisfactorily approximated by a normal distribution [36]. For the assumption of the independence of residuals, the Durbin-Watson Statistics can be considered. Since this has the value 0.99 (approximate to 1), it is expectable that the residuals are correlated. It can be explained by the existence of a sequence of billets being extruded in the process, which are easily welded together at the extrusion temperature and pressure [24,26]. The values of tolerance and Variance Inflation Factor (VIF) for each independent variable are in Table 2, which shows that there is statistical evidence to support the inexistence of multicollinearity. Taking into account everything that has been stated before, the assumptions of the linear model are validated. However, methods can be used in future and compared with this model.

4. Conclusions and Future Work

In this work, a multivariate linear regression model to predict the amount of scrap produced depending on a set of extrusion conditions, is proposed. Real data from a Portuguese company in the extrusion aluminium sector was used. The results show that variables concerning with extrusion temperature, time, ram speed, pressure and die geometry are crucial to improve and control the scrap production. In particular, the amount of scrap is higher with the increase of the dead time, E_t_D, extrusion time, E_t, speed time, E_t_S, sealing pressure, E_p_{SL}, billet length, E_L_B, length butt, E_L_{Butt}, number of holes, E_NH, extrusion specific weight, E_SW. The amount of scrap is greater with the increase of the post container temperature, $E\_T_{C,P}$, extrusion end temperature, E_T_{End}, extrusion speed, E_S_C and extrusion pressure max (bar), E_p_{Max}.

The future work consists on studying the variables that were not considered in the model here presented. These variables may be included in pre and post-extrusion. We aim at accessing if the inclusion of other variables may improve the multivariate linear regression model developed so far. We also intent to include the defects in production and where they come from. Furthermore, grouping the independent variables using factor analysis and performing linear regression of the factors obtained with this methodology can also be a possibility to improve the analysis. Another possibility for future work is the application of the GHLM model.

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