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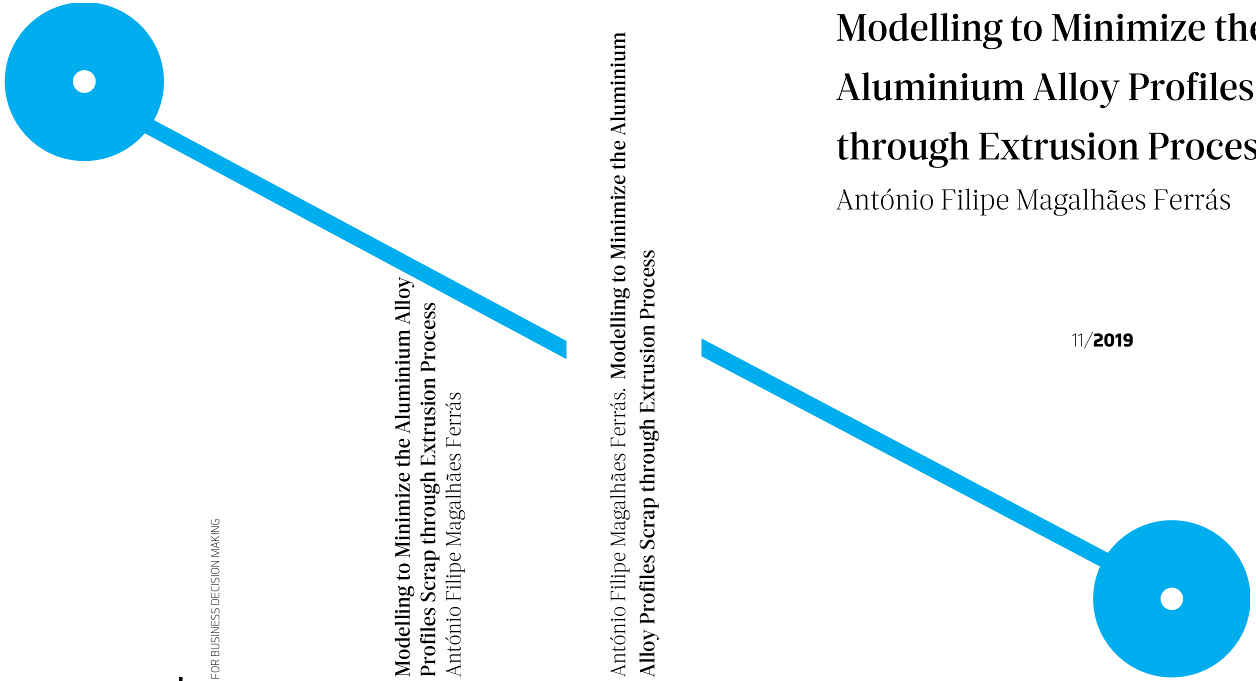
Modelling to Minimize the Aluminium Alloy Profiles Scrap through Extrusion Process

António Filipe Magalhães Ferrás

11/**2019**



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Supervisors
PhD Aldina Isabel de Azevedo Correia
PhD Maria de Fátima de Almeida Ferreira
PhD Eliana Oliveira da Costa e Silva

"A maior recompensa pelo nosso trabalho não é o que nos pagam por ele,
mas aquilo em que ele nos transforma"
(John Ruskin)

Aos meus pais...

Jury

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Resumo

A investigação em tecnologia de extrusão tem vindo a ser alvo de vários estudos, focada principalmente em obter melhores parâmetros e propriedades de extrusão. Os problemas de otimização surgem em vários domínios económicos e, apesar da grande variedade de estudos presentes na literatura, poucos são os que retratam a sua resolução com dados reais do setor metalúrgico.

O presente projeto tem por base o desafio proposto por uma empresa portuguesa do setor metalúrgico que consiste na otimização de processos avançados na extrusão de alumínio. Para tal, a empresa propõe como objetivo principal modelar o processo de extrusão de alumínio, em particular minimizar a quantidade de sucata produzida, tendo em conta as várias variáveis intervenientes no processo.

Na indústria metalúrgica a extrusão é o processo de eleição, dado não só o alto lucro a que pode conduzir, mas também às qualidades dos materiais produzidos por extrusão. O foco deste estudo são as fases de Pré-Extrusão, Extrusão e Pós-Extrusão, sobre as quais incide a base de dados disponibilizada pela empresa. Assim, para dar resposta ao desafio foram fornecidos pela empresa dados relativos à extrusão industrial, referentes à produção do primeiro semestre do ano de 2018, registados durante a produção contínua de vários perfis de alumínio. O estudo resulta em dois artigos.

O primeiro incide sobre a fase de extrusão, tendo como objetivo determinar quais as variáveis envolvidas no processo de extrusão que possam ser controladas, de forma a ir de encontro ao objetivo definido: reduzir a produção de sucata durante o processo de extrusão de alumínio. De seguida, são definidos uma série de valores possíveis de alterar, que permitem controlar e otimizar esta fase do processo. Estes dados foram sujeitos a modelação estatística, através de regressão linear múltipla, que permite prever a quantidade de sucata produzida, dependendo de um conjunto de condições de extrusão. Otimizando desta forma a quantidade útil de matéria-prima e a qualidade do produto, garantindo a sua adequação às especificações do cliente.

No segundo são abordadas todas as fases do processo de extrusão de alumínio, desenvolvendo-se um plano que permita um controlo das variáveis envolvidas em todo processo. Deste plano faz parte a seleção de perfis mais frequentes e de perfis com indicadores mais significativos na produção de sucata. De seguida, são definidos os valores possíveis de alterar, que permitem controlar e otimizar todo o processo. Estes dados permitiram obter ferramentas para construir um modelo de otimização das variáveis de extrusão, nesta indústria de alumínio e ainda foram sujeitos a modelação estatística, através de regressões lineares múltiplas. Otimizando a quantidade de sucata produzida, o lucro da empresa também sofrerá um aumento e, além disso, tornando-a energeticamente mais sustentável.

Como tal, é importante salientar que na indústria metalúrgica, a questão ambiental é cada vez mais analisada, sendo fulcral o controlo de impactos ambientais negativos, preservando o consumo de energia e recursos naturais.

Os resultados mostram que é possível minimizar a produção de sucata na empresa, aumentando a sua sustentabilidade, com pequenas medidas de correção das variáveis controláveis. Otimizando o processo de extrusão de alumínio, seja na diminuição de desperdício ou aproveitando ao máximo a combinação única de características físicas do alumínio, a empresa está a contribuir para um melhor ambiente. Além disso, a vantagem da possibilidade da reciclagem total do alumínio desperdiçado, em combinação com a otimização do processo, é possível e recomendada.

Palavras Chave: Extrusão de Alumínio; Otimização de Sucata; Sustentabilidade; Variáveis de Extrusão; Regressão Linear Múltipla.

Abstract

Research on extrusion technology has been the subject of several studies, focusing mainly on obtaining better extrusion parameters and properties. Optimization problems arise, then, in various economic domains and, despite the wide variety of studies in the literature, few portray its resolution with real data from the metallurgical sector.

This project is based on a challenge proposed by a Portuguese company in the metallurgical sector which consists in the optimization of advanced aluminium extrusion processes. To this end, the company proposes as its main objective to model the aluminium extrusion process, in particular to minimize the amount of scrap produced, taking into account the various variables involved in the process.

In the metallurgical industry, extrusion is the process of choice, given not only the high profit it can lead to, but also the qualities of the materials produced by extrusion. The focus of this study is the Pre-Extrusion, Extrusion and Post-Extrusion phases, which are included in the database provided by the company. Thus, to meet the proposed challenge, the company provided industrial extrusion data for the first half of 2018 during the continuous production of various aluminium profiles. The study results in two papers.

The first focuses on the extrusion phase, aiming to determine which variables involved in the extrusion process can be controlled, in order to meet the defined objective: to reduce scrap production during the aluminium extrusion process. Then, the values that can be changed are defined, which allows to control and optimize this phase of the process. These data were subjected to statistical modeling, through multiple linear regression, which allows to predict the amount of scrap produced, depending on a set of extrusion conditions. Optimizing the useful quantity of raw material and product quality, ensuring its suitability to customer specifications.

In the second one, all phases of the aluminium extrusion process are covered, and a work plan is developed to allow a control of the variables involved in the whole process. This plan includes the selection of more frequent profiles and profiles with the most significant indicators in the production of scrap. Then the values that can be changed are defined, which allow to control and optimize the whole process. These data allowed us to obtain tools to construct an optimization model for the extrusion variables, in this aluminum industry and were subjected to statistical modeling through multiple linear regressions. Optimizing the amount of scrap produced, an increase of the company profit would be observed and, besides that, the company's is making more energy sustainable.

As such, it is important to point out that in the metallurgical industry, the environmental issue is increasingly analyzed, and the control of negative environmental impacts is crucial, preserving the consumption of energy and natural resources.

The results show that it is possible to minimize scrap production in the company, increasing their sustainability, with few corrective measures. Optimizing the aluminum extrusion process, reducing waste or making the most of the unique combination of aluminum's physical characteristics, the company is contributing to a better environment. In addition, the advantage of the possibility of total recycling of aluminum waste in combination with process optimization is possible and recommended.

Keywords: Aluminium Extrusion, Scrap Optimization, Sustainability, Extrusion Variables, Multiple Linear Regression.

Contents

Acronyms

ALE	Arbitrary Lagrangian–Eulerian
DW	Durbin–Watson Statistcs
EAA	European Aluminium Association
ER	Extrusion Ratio
FEM	Finite Element Method
FVM	Finite Volume Method
GHLM	Generalized Hierarchical Linear Model
ISO	International Organization for Standardization
KPIs	Key Performance Indicators
K–S	Kolmorogov–Smirnov
LCA	Life Cycle Assessment
LTI	Lost Time Incident rate
OSHA	Occupational Safety and Health Administration
SDIs	Sustainable Development Indicators
SW	Shapiro–Wilk
TRI	Total Recordable Incident rate
VIF	Variance Inflation Factor

Chapter 1

Introduction

The Eco-efficiency and sustainability plays an important role within organizations, both for safeguarding the environment, through the awareness of power and society, as for the competitiveness of companies [12, 15]. Environmental sustainability in production processes is an pivotal and remarkable issue and the main concerns are related to more efficient use of materials and energies [8].

Management throughout its evolution has become more complex and it is present in organizations and businesses as a challenge [10]. However, the efficient management, is increasingly seen as a source of competitive advantage for any organization [19]. Therefore, optimized decisions become a strong competitive argument and of the utmost importance to managers, in order to ensure the profit and sustainability of the company.

However, the aluminum industry is natural resource intensive consumer and has a substantial role in the surrounding environment changes, and sometimes with negative impact into the environment. Although with environment impact, the extrusion is one of the major metal forming processes. It 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) [14]. Extrusion is used to transform an ingot into an useful product, with the size and shape required, allowing to manufacture very varied geometry components [4], with application in numerous industries and making use of a wide range of metallic materials, of which stand out, because of its importance, aluminum alloys [14].

Aluminum (chemical element with symbol Al) is a metal obtained from the ore called bauxite and has been at the service of the industry for more than 150 years. Being the most abundant metal in the Earth's crust, which constitutes approximately 8.5% [3], in its pure form, this metal is ductile and soft. Most metal elements form alloys with aluminum. However when connected to other elements its resistance can be fifty times higher than in its pure form. Aluminum alloys can be divided into alloys for foundry and in alloys for mechanical work, and can be treated thermally [16].

The multiplicity of applications is evidenced by that aluminium profiles can have in sustainable construction, particularly in the area of home automation and renewable energy [2]. The properties of the extruded aluminum shapes are affected greatly by the way in which the metal flows during extrusion. A feature that identifies this metal is, aluminum alloys for mechanical work are classified according to their composition, using a four-digit designation. The first digit indicates the main alloy element, and the digit 1 is reserved for the unbounded aluminum. The last two digits indicate the aluminum alloy or, for pure aluminum, the degree of purity. The second digit indicates the original alloy composition modifications or impurities limits [16].

Throughout time, aluminium alloys have been widely studied and developed. One factor for this to happen is their exceptional properties: flexible and versatile; sturdy and durable; innovative and affordable; practical and effective; thermal conductor and acoustic insulator; easy to recycle [3, 5, 14, 18].

As such, the role of this research is to support decisions related to this process, suggesting tools to minimize the amount of scrap produced in the extrusion process, through a data analysis and a quantitative approach. A process modeling is proposed and the variables that can be adjusted are identified, and improvements can be suggested.

1.1 The Company

The company under study is the ADLA Aluminium Extrusion S. A. [2]. It was founded in 2011, is an young Portuguese company, of the industrial sector, dedicated and specialized in the development and production of aluminium profiles, whose core-business is aluminium production. The process goes from extrusion to commercialization and treatment of aluminium profiles, through the assembly of profiles with thermal rupture and the development of various solutions for application in architecture and industry. It has facilities equipped with a 2500 Ton press, production capacity of 800Ton/month and allowing to produce profiles with 320 mm x 20 mm and weighing up to 25kg/m.

The aluminium extrusion is a process in which a press forces a cylindrical aluminium billet against a die, forming products of constant section. With innovation as its main orientation, the company has developed several control systems for quality, in particular the three-dimensional analysis of aluminium profiles, which allows the checking of the occlusions that the parts may present. Inserted in a demanding market, its main pillars are quality (ISO 9001: 2008 certified company since 2013), innovation, technology and environment (company certified according to ISO 14001: 2008 since 2016). This company appears as the productive link and exporter of the business group to which it belongs, integrating, in view of the existing situation, the productive part and the international side.

In the company under study, the aluminium billets are stored in batches, according to the alloy and the supplier. After the production planning, the production system starts the extrusion process of the profiles. There is a first visual, dimensional quality check and confirmation of the quality certificates that come with the billets. When a batch is selected for extruding, the billets are transported to the feed ramps and the process starts with a simple cleaning of the surface, to remove dirt and some surface impurities, that may exist. After being cleaned, the billets enter the preheating furnace, where they are heated in a most homogeneous way. The extrusion is prepared by heating the billet according to the specified alloy and the dies already prepared. This gas-fired oven consists of five heating zones allowing gradual heating and avoiding that the billet is exposed to high temperatures for an extended period of time, and, on the other hand, to thermal gradients (temperature differences throughout the billet). Prior to extrusion the die is also heated to prevent thermal shocks. At the exit from the oven the billets are cut and transported to the press container, which remains heated to a constant temperature. Then, the billet is extruded. At the die exit the profiles can be cooled down by air or water, depending on the alloy and the profile. Normally the profile is pulled by a puller, which guarantees a constant output speed in order to ensure a regular product. When coming out the press the profiles are inspected visually, the production control register is completed and if they meet the specifications the production order continues. Otherwise, they are rejected, the nonconformity is recorded and forwarded to the quality department. In the same production series, the profiles are extruded continuously, being cut with hot saw to each billet that is pressed. This cut is precisely made from the area where a billet joins the previous one. The profile, already cut, is attached at both ends and is stretched, so that it is straight and without curvatures. The zones next to the splicing of the billets are eliminated (scrap), since they are zones of great heterogeneity. After passing in the stretcher, the bars are cut into bars of lower length and placed in containers, which are transported to the aging furnaces, if the profiles are aged, or for shipment. The profiles, after aging, can also undergo an anodizing or lacquering surface treatment, according to the customer's requirements. Then, the product go to the packing section to ship to the customer.

However, the initial conditions of the billet are crucial for good extrudability and for a final product with the desired properties and qualities, from mechanical properties, to response to subsequent heat treatments and surface treatments, to surface quality and adhesion of paints or coatings. The company's focus is to have production capacity that can be applied to a variety of eco-efficient solutions, while simultaneously activating design concerns, resource efficiency and use of materials and products.

1.2 The Case Study

The present work focuses on the optimization of advanced aluminum extrusion processes, in the studied company ADLA Aluminum Extrusion SA. The main objective is to model the aluminum extrusion process, in particular to minimize the amount of scrap, taking into account the various variables involved in the process. Improving the production of aluminum profiles, as efficiently and profitably as possible, and using the least amount of natural resources, is the ultimate goal to be achieved.

For the study, a database concerning with the production in the period from January to June 2018, provided by the company, was considered. As specific objectives are considered:

- To study the effect of the process variables, in particular related with temperature, speed, time, pressure and geometry;
- To maximize the useful quantity of raw material;
- To minimize the amount of scrap produced in the process;
- To improve product quality to customer specifications;
- To increase the company's profit;
- To rise the company's energetically suitability;

for that an optimization model and multiple linear regression models were developed, using the data provided by the studied company.

Thus, we consider the continuous production of the various aluminum profiles produced by the company in the pre-extrusion, extrusion and post-extrusion phases.

Specifically, the company seeks to find a way to know which optimal values to assign to each variable in each phase of the process in order to decrease scrap production throughout the extrusion process and increase sustainability and production efficiency. Not forgetting the resource efficiency and durability of materials and products.

In addition, another important factor in optimizing the entire process is to provide to the operators and to the managers adequate indicators that allow the control of the production process and the identification of critical extrusion variables (or others), responsible for excess of waste and defects, in order to increase productivity.

1.3 Contributions of this Project

Optimization problems arise in various economic domains, but despite the wide variety of studies in the literature, few of them portray their resolution with real data from the metallurgical sector. Most works found in the literature use simulated data, this because, traditional approaches that simulate the whole extrusion process are often costly and time-consuming [9]. Thus, the possibility of working a real problem of the aluminum industry, with real data provided by the company, makes this an interesting project.

The growing number of publications and studies leading to the aluminum industry make clear its importance over the years. The credibility of the aluminum sector depends on the environmental sustainability built into the entire production process [5], being that, the main concerns relate to the efficient use of materials and energy [8, 12, 17].

Thus, it is increasingly recognized that the process must be controlled to ensure product and customer's specificities, as well as the minimum scrap production [1, 13].

Industry specificities require the design of a tailored solution, the present work provides operators and managers with adequate indicators that allow controlling the extrusion process through critical extrusion (or other identified) variables, responsible for excess waste and defects, in order to increase productivity.

Not neglecting, the three main streams in the development of today's environmental strategy are pointed out by Paraskevas [13]: Cleaner production, eco-industry and circular economy. The three focuses on the inevitability and rationality to extend environmental management into all the relevant aspects of organization, enterprise group and national economy.

As such, it is important to point out that in the metallurgical industry, the environmental issue is increasingly analyzed, and the control of negative environmental impacts is crucial, preserving the consumption of energy and natural resources [12, 17].

The main contribution of this project is the development of quantitative methods based on optimization and multivariate statistics that contributed to meet the company's challenge, and if possible, scale-up to other industries. Bearing also into account strategic economic and social development policies of eco-sustainability, which are devoted to save environment and natural resources.

1.4 Structure

This dissertation is organized in four chapters: 1) Introduction; 2) Scrap Production of Extruded Aluminum Alloys by Direct Extrusion; 3) Minimize the Production of Scrap in the Extrusion Process; 4) Conclusion and Future Research, as depicted in Figure 1.1. The chapters 2 and 3 are papers, that were carried out during this project.

Figure 1.1: Structure of the project

The chapter 1, Introduction, portrays an overview of aluminum extrusion and the importance of sustainability in the industrial sector. Next, the Portuguese company under study is presented, as well as its production process. In the following section, the case study is presented, identifying the main objective and the specifics objectives of the proposed challenge. Consecutively, supported by the research, the contributions of the current project are presented. Finally, the project structure and it organization is descrived.

The Chapter 2 consists of the paper entitled "Scrap Production of Extruded Aluminum Alloys by Direct Extrusion" presented at the FAIM2019 – 29th International Conference on Flexible Automation and Intelligent Manufacturing, accepted for publication in the *Journal Procedia Manufacturing*, [6]. It includes a literature review on the subject of aluminum extrusion, focusing only on the extrusion phase of the process. A literature review that identifies the variables that most influence the extrusion process was made. Then, the company's actual data were modeled using a multiple linear regression, which made it possible to predict the amount of scrap produced, depending on a set of extrusion conditions. Besides that it was possible to indicate the variables with most contribution to scrap production and, consequently, indicate the best choice of parameters to extrusion. Optimizing, thus the useful quantity of raw material and product quality, ensuring its accordance to customer specifications.

Chapter 3 includes the paper entitled "Minimize the Production of Scrap in the Extrusion Process". In this paper, all phases of the aluminum extrusion process were considered. In a first study, the variables that affected all stages of the process were analyzed for all profiles produced by the company under study. Next, 18 profiles were studied, the 9 most produced and the 9 most produced and most scrapped. Then the values that can be changed are defined, allowing to control and optimize the whole process. The data were modeled using multiple linear regressions, providing tools to build a model for the optimization of extrusion variables in the aluminum industry. Optimizing the amount of scrap produced, the company's profit is improved and making it sustainable in energy.

Finally, Chapter 4 presents the conclusion, and suggestions for future works to be developed.

Chapter 2

Scrap Production of Extruded Aluminum Alloys by Direct Extrusion

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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.

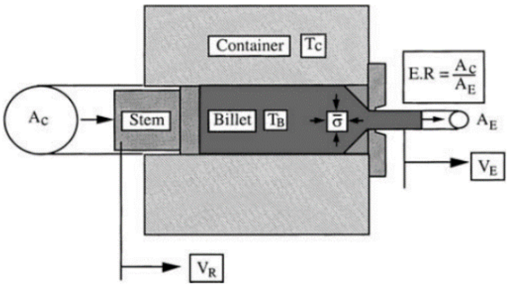

Fig. 1 - Extrusion variables [2].

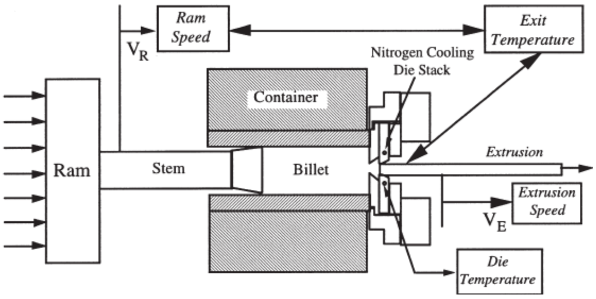

Fig. 2 - Temperature and speed control extrusion [2].

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 has 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.

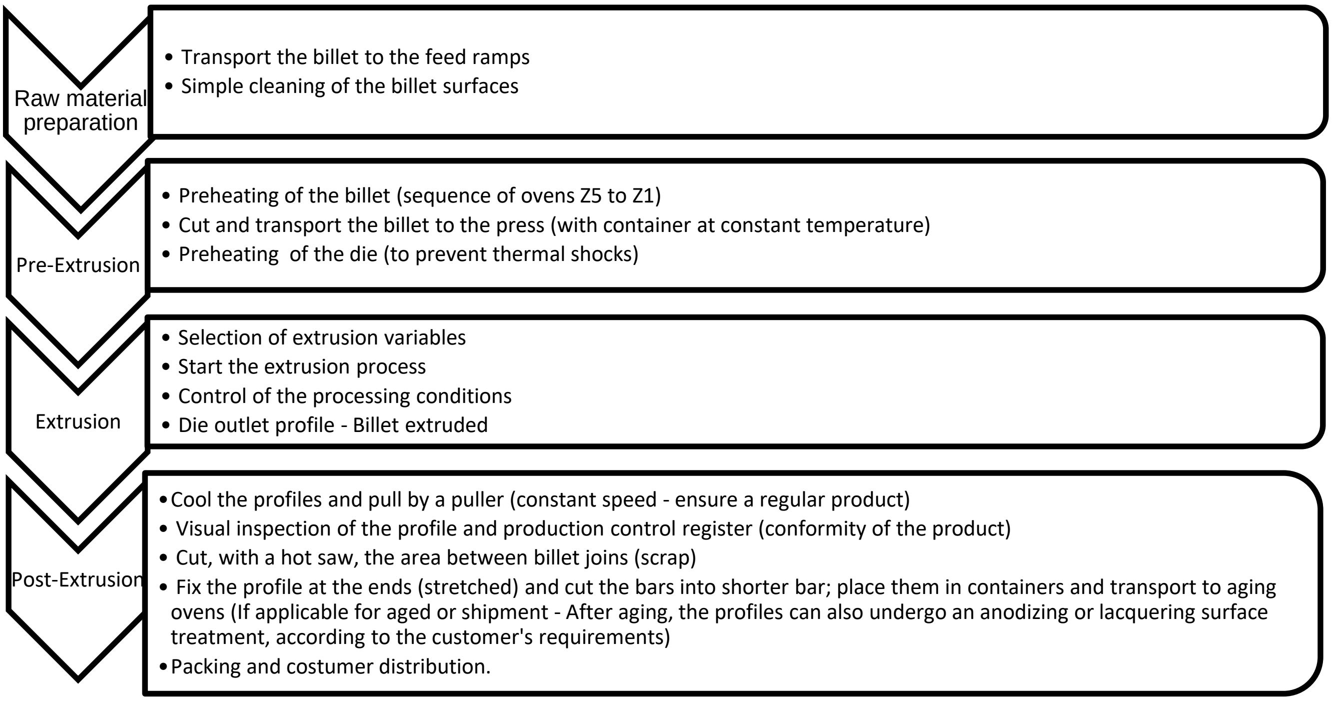

Fig. 3 - The company extrusion process [28].

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},

$$\mathrm{SC_{KG}} = \mathrm{PR\_W_B} - \mathrm{PO\_W_B}. \quad (1)$$

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 (°C); $\mathrm{E\_T_{End}}$: Extrusion End Temperature (°C);
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 $\mathrm{E\_t_S}$ and negatively by the variable E_S. With the analysis of the coefficient of the variables $\mathrm{E\_p_{SL}}$ and $\mathrm{E\_p_{Max}}$ it is possible to see statistical evidence confirming **H4**, and the amount of scrap greater the lower is $\mathrm{E\_p_{Max}}$ and inversely is greater the upper the $\mathrm{E\_p_{SL}}$. The extrusion ratio, having into account the coefficient of the variables, $\mathrm{E\_L_B}$, $\mathrm{E\_L_{Butt}}$, 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		
	$\mathrm{E\_t_D}$	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
	$\mathrm{E\_T_{C,P}}$	-0.21	0.01	-0.09	-23.35	0.00	0.83	1.21
	$\mathrm{E\_p_{Max}}$	-0.06	0.00	-0.12	-22.58	0.00	0.47	2.15
	$\mathrm{E\_L_{Butt}}$	0.12	0.01	0.06	15.61	0.00	0.89	1.12
	$\mathrm{E\_L_B}$	0.01	0.00	0.06	13.12	0.00	0.53	1.87
	$\mathrm{E\_t_S}$	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
	$\mathrm{E\_T_{End}}$	-0.01	0.00	-0.02	-5.20	0.00	0.86	1.17
	$\mathrm{E\_p_{SL}}$	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:

$$\mathrm{SC_{KG}} = 57.54 + 1.31E\_t_D + 1.47\mathrm{E\_SW} + 0.04E\_t + 0.67\mathrm{E\_NH} - 0.21\mathrm{E\_T_{C,P}} - 0.06\mathrm{E\_p_{Max}} + 0.12\mathrm{E\_L_{Butt}} \\ + 0.01\mathrm{E\_L_B} + 0.01\mathrm{E\_t_S} - 0.24\mathrm{E\_S} - 0.01\mathrm{E\_T_{End}} + 0.08\mathrm{E\_p_{SL}} \qquad (2)$$

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, $\mathrm{E\_t_D}$, extrusion time, E_t, speed time, $\mathrm{E\_t_S}$, sealing pressure, $\mathrm{E\_p_{SL}}$, billet length, $\mathrm{E\_L_B}$, length butt, $\mathrm{E\_L_{Butt}}$, number of holes, E_NH, extrusion specific weight, E_SW. The amount of scrap is greater with the increase of the post container temperature, $\mathrm{E\_T_{C,P}}$, extrusion end temperature, $\mathrm{E\_T_{End}}$, extrusion speed, $\mathrm{E\_S_C}$ and extrusion pressure max (bar), $\mathrm{E\_p_{Max}}$.

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.

Acknowledgements

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Chapter 3

Minimize the Production of Scrap in the Extrusion Process

Minimize the Production of Scrap in the Extrusion Process

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Abstract

In the discussion on environmental policies, the notion of eco-efficiency is often used. Eco-efficiency is defined as the delivery of products and services with competitive values, while reducing the ecological impacts and satisfying human needs.

In an environment of great competitiveness in which the companies operate, the improvements in the productive process is one of the differentiating factors for guaranteeing a strong competition. Also it is essential rationalizing energy consumption and natural resources. For this it is necessary to understand the main operations and dynamics of the company.

This work presents an empirical study of a Portuguese company in the industrial sector. The problematic here presented is based on the company's growing concern to reduce the amount of scrap produced. From the literature research that was performed, a strong dependence relation between the different variables in the extrusion process was found. The main objective of this work is to model the aluminium extrusion process, with the aim of minimizing the production of scrap. For this several variables involved in the process are taking into account. Using statistical techniques, in particular multiple linear regressions, it was possible to identify the importance of the variables under study for the scrap production.

Keywords: Aluminium Extrusion, Scrap, Sustainability, Extrusion Variables, Multiple Linear Regression.

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1 Introduction

The complexity and heterogeneity of industries make their analysis essential. The correct management of organizations is crucial for their survival. In the area of Environmental Policies, the Sustainability and the Eco-efficiency issues are becoming increasingly important, both for safeguarding the environment, through the awareness of power and society, as for the competitiveness of the companies [36, 45].

Rapid economic growth and the industrialization process inevitably led to resource depletion and environmental degradation [52]. In order to prevent this, different approaches are currently adopted in several countries [13]. Environmental sustainability in production processes is an urgent and remarkable issue and the main concerns are related to a more efficient use of materials and energy [17, 23, 36, 48]. In the aluminium industry, business units want to produce innovative profiles, either by size or increased energy efficiency capacity, with complex industrial processes. For that, complex an innovative industrial processes are used and optimized every day. The demand for an efficient and sustainable use of energy and resources has led to new design criteria for technical products [17]. This focus is evidenced by the multiplicity of applications that aluminium profiles can have in sustainable construction, particularly in the area of home automation and renewable energy [2].

An increasingly demanding industry promotes the dynamic between high quality and low prices, without losing product specifications, leading to new industrial challenges. Besides that, manufacturing industries are focused on controlling negative environmental impacts, reducing costs, conserving energy and natural resources. In this context, the industry is an intensive consumer of natural resources [32], and has a substantial role in the surrounding environment changes, that sometimes has a negative impact in the environment. Reducing CO_2 emissions is an urgent objective to pursue [5, 24]. In modern society some environmental issues linked to the industry are part of the most significant threats to sustainable development [32].

The incessant pursuit of success is the core objective of any company, only possible if it is integrated into a supported strategic management system. Management throughout its evolution has become more complex and has been presented in organizations and businesses as a challenge [31]. Planning consists in defining in advance a set of actions or intentions to perform in the future. It is based on this set of programmed activities that companies design and sustain their management strategy.

In the metallurgical industry, extrusion is a first-line technique [43], which is very popular and a multi-faceted manufacturing process [40]. For the most demanding applications on the market it is important to predict/control the properties of aluminium in extrusion process, if possible, before, during and after extrusion. Hence, it is necessary to gain information about the influence of technological parameters [16]. Extrusion offers unique construction and design possibilities, with different functional characteristics [21, 43, 46, 51]. Also, it is an extremely complex process associated with several variables, from numerous sources and in the various phases of the process, and must be controlled to ensure product and customer's specificities, as well as the minimum scrap production [1, 39].

The main objective of this article is to present a model that minimizes the amount of scrap generated in the production sector of an extrusion Portuguese company. It is intended to improve the process, and draw attention to environment protection, improving behaviours, attitudes and practices, with the potential to contribute to the development and competitiveness of the company in this important industrial sector. The present study was based on linear regressions analysis to optimize the entire extrusion process of the company under study, in particular by minimizing scrap production in the metallurgical sector. The real database provided by the company includes information concerning the three phases of the production process under analysis, i.e. pre-extrusion, extrusion and post-extrusion. It is expected that these variables contribute to explain the scrap variability by the independent variables included in the linear regression model.

The paper is organized as follows: in Section 1, the subject is contextualized; Section 2, presents a brief literature review on the aluminium extrusion process, describing the importance of sustainable production, combating the wastefulness of waste, that can be recycled at high cost. The methods that are most commonly used to simulate the extrusion process are presented and finally it is presented an optimization model that has applicability to the study. In Section 3, it is presented the empirical study and the proposed multivariate models, as well as the validation and discussion of the industrial process problem model. This paper concludes with a discussion of the main findings and suggestions for future work, in Section 4.

2 Literature Review

The extrusion industry is over 150 years old. Aluminium is one of the most abundant metals in the earth's crust. Although there is a great abundance of this metal in nature, it does not appear as an isolated element but in combination with other metals. The Bayer process allows aluminium to be extracted from these materials, which is a major step forward in the use of this metal at industrial level [49].

Furthermore, aluminium extrusion technology in industry, continues to be a subject of discussion and evaluation, concerning its application to the working environment in the most diverse industrial areas and markets, such as construction, transport, motor sports, industry and structures, a large number of different applications of extruded aluminium profiles can be found [33, 40, 43].

Extrusion is a plastic deformation process very versatile in which a billet is forced to flow by compression through the die opening of a smaller cross-sectional area than that of the original billet [43]. Long straight metal parts can be produced. Mostly hot direct extrusion is applied to produce solid and hollow profiles of light alloys [16]. In Figure 1, an extrusion process similar to the company one under study it is presented.

Extrusion can be cold or hot [43]. Cold extrusion is the process done at room temperature or slightly elevated temperatures. Nevertheless, hot extrusion is done at fairly higher temperatures at the melting point of the metal. The melting point depends on the alloy and the method used. Nevertheless, between the two main types of extrusion: direct and indirect, the most common for the production of aluminium profiles is direct extrusion [49].

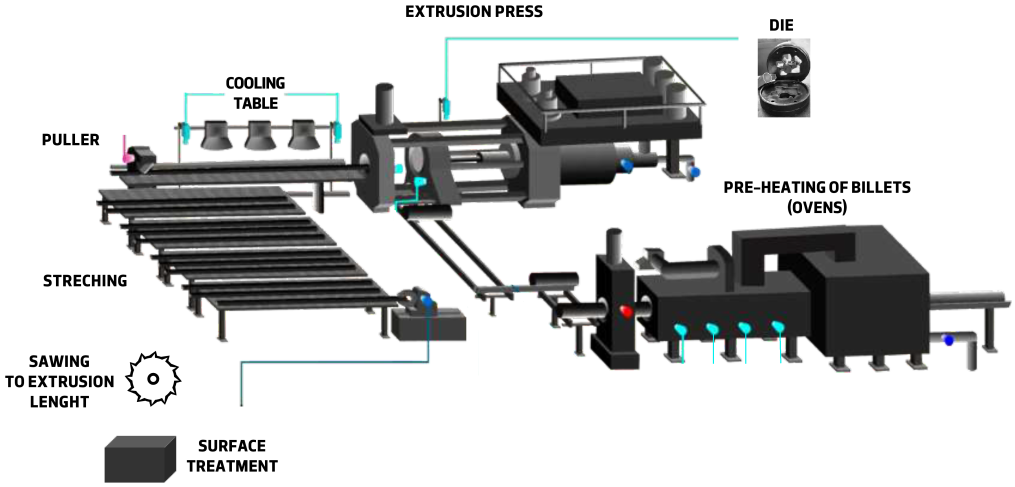

Figure 1: The extrusion process [3]

The extrusion technology allows manufacturing a width variety of geometry components [4]. In this industrial process, several parameters, such as, temperature, time, velocity, pressure and geometry, must be well adjusted for each alloy type.

Speed and temperature parameters are considered the key variables to maximize productivity. However, the acceleration time also helps to reduce the total extrusion cycle time and increase productivity [43]. In [39, 43], different ways to reduce the cycle time of each alloy and billet size are shown.

Furthermore, temperature is one of the most important parameters in the extrusion process [33]. The billet temperature, for Laue [27], is recommended to operate at 420–430 °C. Temperatures above these temperatures would cause profile defects, leading to scrap production. According to Marín's study in [33], the higher the die or billet temperature, the lower the load to perform the process. In addition, optimum mold and billet temperatures allow for greater efficiency of the hot extrusion process and result in better quality products.

In the study by Lombardo [30], using sequential casting of two aluminium alloys, two important variables are considered to optimize the process: the order of leakage and the waiting time between alloy leaks. These are parameters related to casting temperature, die geometry and alloy compositions.

The extrusion pressure, for Ikumapayi [22], is influenced by the geometries of the billet and of the die, and also by extrusion variables, such as, ram speed. For Saha [43], the required pressure for extrusion could vary with the alloy and its condition, length and billet temperature, extrusion speed, the extrusion ratio, and circumscribed circle diameter.

The critical variables that influence the force required for extrusion and the quality of material, according to Saha [43] are:

- Extrusion Ratio ($E.R.$);
- Working Temperature (T_B);
- Speed of Deformation (V_R);
- Alloy Flow Stress (σ).

In line to this vision, Bajimaya [6], verified 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 ($E.R.$).

For Qamar [20], die and tooling defects are one of the major sources of product defects, so detection and mitigation of product defects are very important in maintaining the productivity and profitability.

Surace [50] investigated the influence of processing conditions on relative density and strength. Correct adjustment of extrusion parameters is necessary to obtain the appropriate and desired mechanical properties [6, 8, 15]. Thus, with a proper flow control, better mechanical properties can be obtained by preserving the material orientation [26]. Across:

- Reduction of friction, allowing extrusion of larger billets, enhanced speed, and an increased ability to extrude smaller cross-sections;
- Less tendency for extrusions to crack as no heat formation takes place from friction;
- Container liner lasts longer, due to less wear;
- More uniform use of billet ensures that extrusion defects and coarse grained peripherals zones are less likely.

The extrusion process makes the most of aluminium's unique combination of physical characteristics [1]. No other metal can match the sustainability advantage of aluminium or its combination of useful physical properties such as: strength, durability, flexibility, impermeability, devaluation, corrosion resistance and recyclability [3, 13, 43, 50]. An increasingly demanding industry promotes the dynamic between high quality and low price, without loss of product specifications, leading to new industrial challenges. Besides that, manufacturing industries are focusing on controlling the negative environmental impacts, reducing cost, conserving energy and natural resources, while producing new products through various methods and tools of sustainable manufacturing assessment [36, 48].

Studies indicate that 60% of the earth's land area is managed by man, however 100% of planet earth is affected by Human actions [42]. In fact, as economies grow, they tend to use more resources. Driven by industrial and technological development and changing consumption patterns, resource extraction has increased 10 fold since 1900 and may double by 2030 [18]. This shows that in order to achieve sustainability, there is the need of holistic optimization of the entire environment [1]. This is a challenge that everyone shares and is responsible for solving [18]. For Thiede, quoted by [23] the environmental issues, as well as, energy consumption and new sources of energy are increasingly seen as crucial concerns in industrial production.

2.1 Sustainability

Sustainability has become a buzzword both in today's business world and on the broader faces of society. Environmental sustainability in manufacturing industry is a pressing and urgent issue. The main concerns relate to the efficient use of materials and energy [23, 36, 48]. The notion of sustainability notion became known worldwide in 1987 through the Report Designated as *Our Common Future* (known as the Brundtland Report) [7]. The Triple Bottom Line framework is rooted in stakeholder theory, organizational management theory, and business ethics [19]. A sustainable company is one that contributes to sustainable development by offering economic (profit), environmental (planet) and social (people) benefits.

In 1992, the "Agenda 21" document appeared as global program to which 118 countries joined and whose main objective was the promotion of environmental regeneration and social development. With a global action plan but local actions, since even small actions make a difference [47].

Twenty years later, at the Rio + 20 conference, a new document entitled "The Future We Want" was endorsed. Following the negative balance of the world leaders from the previous period, the document aims to reinforce the importance of meeting the predefined commitments of the established sustainability goals and strengthening financing for developing countries [35].

The credibility of European Aluminium Industry depends on its efforts to continuously improve its economic, environmental and social performance. The industry's Sustainability Roadmap 2025, launched in 2015, defines a clear and structured sustainability agenda for the aluminium sector in Europe [13].

To measure industry progress towards its objectives in the Sustainability Roadmap 2025, European Aluminium has adapted and enriched its Sustainable Development Indicators (SDIs) already collected and reported regularly since the 1990s [13]. These indicators includes: **i)** Economic indicators, such as Production, Revenues, Capital investments, Value added and R&D expenditure; **ii)** Environmental indicators, such as Plant certification (IOS 14 000), Electricity consumption, other types of energy consumption; and **iii)** Social indicators, such as Plant certification – Occupational Safety and Health Administration (OSHA), safety – Total Recordable Incident rate (TRI), Lost Time Incident rate (LTI), and Fatality rate – and number of employees, etc.

The European Aluminium Industry, through its member organisation the European Aluminium Association (EAA), initiated a program on sustainable development for the aluminium industry in 2001. The first step involved the development of an industry SDIs suite developed in 2001 and 2002 with internal and external stakeholder groups [37].

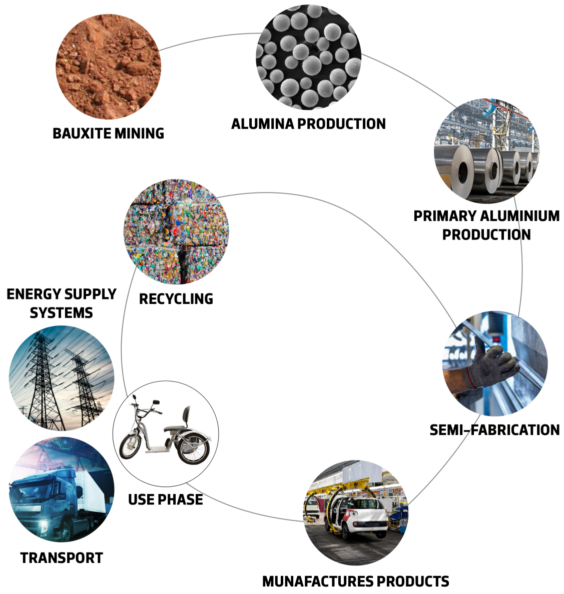

Figure 2: Aluminium Life Cycle [3]

In [29], the authors discuss the state of the practice, the strength, and weakness of life cycle assessments to achieve sustainability goals in the aluminium industry. Figure 2 shows the life cycle of aluminium.

The paper [36] focuses on the technology strategies that lead to radical innovations in aluminium production systems which are important for achieving sustainability goals. In [48], the authors propose science-based guidelines for modelling and evaluating of Key Performance Indicators (KPIs) in an aluminium extrusion process.

Thereby, sustainability is not only about resources, but also about using them efficiently in order to positively improve the effectiveness of the results achieved. Due to constantly increasing green concerns and better performance, lightweight construction is a key factor for success [26].

Corporate sustainable development implies that companies, instead of weighing only their financial results, also seriously consider the environmental and social impacts of their products and services [12, 41].

Eco-efficiency is defined by delivering products and services at competitive values, but also reducing the ecological impacts and meeting human needs [45].

In a circular economy where "extracting, transforming, using and disposing" gives rise to "reducing, reusing and recycling", only environmental challenges awareness will lead to the adoption of behaviours that will promote a low carbon society. According to [18], this is the biggest challenge, i.e.: "change mind-sets to change behaviours".

Environmental concerns in industrial companies are increasingly imperative [9, 37], not only because of national and international norms, but also because of companies' image in current demanding markets. Aluminium industry is no exception. The aluminum industry alone is accountable for approximately 1% of global greenhouse gas emissions [53].

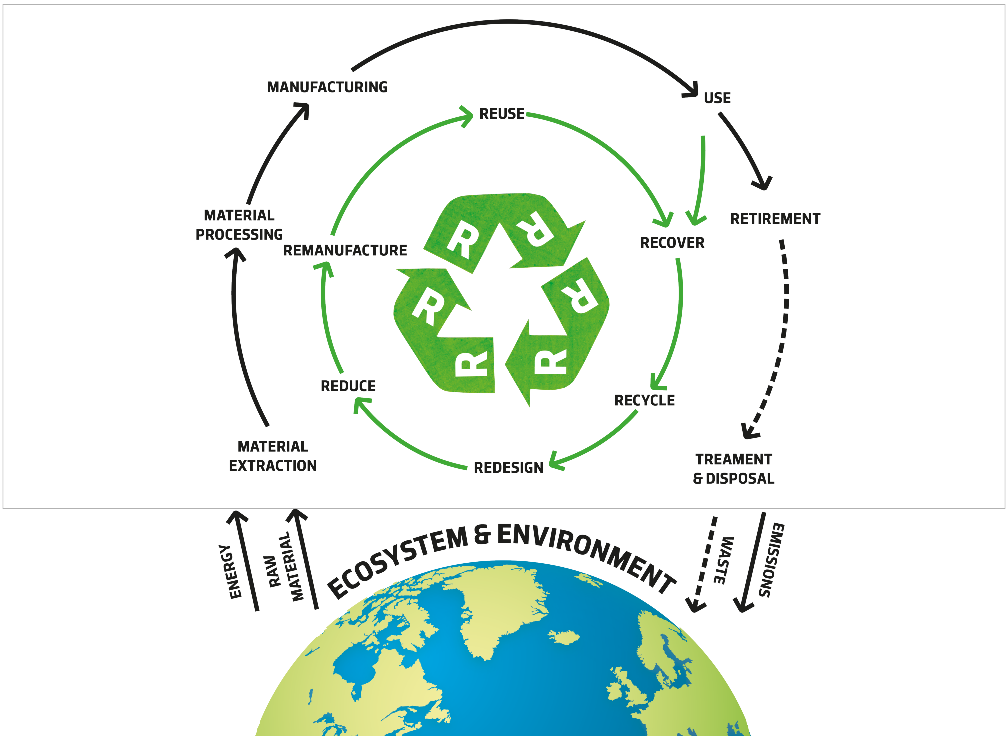

Figure 3: Closed-loop Product Life-cycle System in 6R Approach [1]

Aluminium is 100% recyclable and is the only material that is infinitely recyclable. Figure 3 shows the evolution of different manufacturing concepts and their contributions to stakeholder value, and the proposed [1] closed-loop system involving 6Rs.

Recyclability have spurred new process developments with the goal to obtain materials with a good relation between properties and costs [50]. In particularly, in the case of aluminum, recycling can save a large amount greenhouse gas emissions [53]. During the aluminium scrap melting process, irreversible lost occur. Also, about 12% of the metal is burned and 10% is lost because the aluminium mixes with the slag removed from the surface of the molten metal [44].

High temperature thermal treatment of turnings results in a significant increase of scrap surface oxide films. This is supported by [9] on a study on solid state recycling of aluminium scrap and dross characterization. The authors also found that energy requirement estimations for solid state recycling revealed that the precompaction process uses less than 7% of the energy required for the world's best practice conventional remelting, and resulted in a 93% reduction in carbon dioxide equivalent emissions.

In [23], the authors consider that the main problem that these processes is that they have a recycling efficiency of less than 55%. The amount of scrap produced depends on several processing conditions related to the pre-extrusion, extrusion and post-extrusion processes [15].

Although aluminium is a recyclable material, minimizing scrap production is the best way to avoid excessive costs and preserve the environment. In fact, recycling process is characterized by environmental pollution and high energy consumption [23].

2.2 Methods

According to Jian-Yi, P. *et al.* [25] three numerical methods are widely used to simulate the extrusion process in the literature:

1. Finite Element Method (FEM) based on the Lagrangian formulation – in which the variables of material particles depend on the coordinates and time of the particles.
2. Finite Volume Method (FVM) based on the Eulerian formulation – focuses on the time variable function of particle flow velocity, acceleration and other variables.
3. Arbitrary Lagrangian-Eulerian method (ALE) – which combines the FEM with the FVM and uses two different reference systems to define material flow and mesh movement.

During the various steps of aluminium production, a large amount of scrap is generated due to machining operations. Scrap length due to backend defect depends on different process parameters such as friction, the initial temperature of the billet or tool geometry [20].

In [51], the authors defined design rules for improvements in geometry and functionality of flat and porthole dies. They found that porthole dies results in greater die stability and significant scrap reduction.

Considering die geometry and extrusion speed [38], various extrusion parameters were investigated to determine their effects on the quality of extruded products. The empirical equations show that the non-dimensionalized values of the specific coring pressures and maximum extrusion pressures, depend primarily on the die angle, the load rate and the total reduction in the cross-section area of the complex-shaped section.

Furthermore, aluminium alloy extrusion is recommended to operate at billet temperatures of 420-430°C [27]. Operating above these temperatures would cause profile defects, resulting in scrap metal. Li [28] evaluated the temperature evolution in the extrusion process, by means of a computer simulation of 3D FEM he found that extrusion is limited by two factors: temperature and pressure.

Fang *et al.* in [14], based on the results of simulations using 3D FEM, stated that extrusion speed has a strong effect on extrusion temperature and the latter largely determines the surface quality of the extruded profile. The authors also observed that the effects of die bearing length and extrusion speed on extrusion pressure are negligible. Thus, the extrusion yield is mainly limited by the extrudate temperature rather, not the extrusion pressure.

Compared to the classical discontinuous shear simple model of channel angular extrusion, the new approach allowed to predict effective strain more closely. The flow patterns, extrusion pressure, curvature, and effective strain predicted by the analytical solutions agreed well with the modelling results [54].

Besides that, new modifications and advanced design strategies of alloys and microstructures to improve material properties are considered [21]. The elementary mechanisms of plastic deformation and re-crystallization comprising nucleation and growth and their orientation dependence, within the homogeneously formed micro-structure or due to in-homogeneous deformation, are described along with their impact on texture formation, and the resulting behaviour of formation.

During the extrusion process, it is necessary to ensure the temperature and also the extrusion time are suitable for the extrusion of the material, as both are necessary for complete solubilization [49].

For Qamar [20], many defects in extruded products occur because of the conditions of the dies and tooling. To achieve higher productivity and reduce rework and rejection, it is important to identify more frequent die-related problems and reduce and eliminate their occurrence.

In [15], the possible causes of the high amounts of scrap generated in the production of the aluminium profiles during the extrusion process were studied by estimating multivariate linear regression models adjusted to a set of pre-collected data of a Portuguese company in the aluminium extrusion sector. The results show that variables concerning with extrusion temperature, time, ram speed, pressure and die geometry are crucial for improving and controlling scrap production.

Optimization can be very relevant in process improvement. In [14] an optimisation based method that was used for analysing and improving the yield of aluminium extrusion operations at a local extrusion plant of a company is described. By this very significant savings were obtained, especially when the shape of the extrudate is complex.

2.3 Model

Traditional approaches that simulate the whole extrusion process are often costly and time-consuming [25]. In the methods used, the variables related to temperature, time, velocity, pressure and geometry were considered. Table 1 summarizes the evidences found in literature.

Dimensions	**Literature**
Temperature	Rahim [1], Arif [4], Bajimaya [6], Carvalho [8], Fang [14], Ferrás [15], Ikumapoxi [22], Laue [27], Li [28], Lombardo [30], Marín [33], Saha [43], Soares [49]
Time	Carvalho [8], Ferrás [15], Kleiner [26], Paraskevas [39], Saha [43], Soares [49]
Speed	Rahim [1], Arif [4], Bajimaya [6], Carvalho [8], Fang [14], Ferrás [15], Jian-Yi [25], Marín [33], Saha [43]
Pressure	Carvalho [8], Ferrás [15], Ikumapoxi [22], Li [28], Onuh [38], Saha [43], Zhou [54]
Geometry	Arif [4], Bajimaya [6], Fang [14], Hatzenbichler [20], Ikumapoxi [22], Lombardo [30], Onuh [38], Qamar [40], Vanekes [51]

Table 1: Dimensions according with literature

Dimensions	**Variables**	**Bounds**
Temperature	$T_a, \quad a = 1, \ldots, k$	$l_a \leq T_a \leq u_a$
Time	$t_b, \quad b = 1, \ldots, p$	$l_b \leq t_b \leq u_b$
Speed	$S_c, \quad c = 1, \ldots, m$	$l_c \leq S_c \leq u_c$
Pressure	$P_d, \quad d = 1, \ldots, n$	$l_d \leq P_d \leq u_d$
Geometry	$G_e, \quad e = 1, \ldots, r$	$l_e \leq G_e \leq u_e$

Table 2: Factors for scrap production

Table 2 presents a summary of the factors pointed in literature (c.f. Table 1) as important for scrap production in the aluminium extrusion process.

In this table, $k, p, m, n, r \in \mathrm{N}$, and are defined as:

- k is the number of temperatures measured in the process;
- p is the number of times registered in the process;
- m is the number of speeds monitored in the process;
- n is the number of measures of pressure along the process;
- r is the number of geometric values in consideration.

while

- T_a represents the temperatures measured, for $a = 1, \ldots, k$;
- t_b are the times registered in the process, for $b = 1, \ldots, p$;
- S_c are speeds monitored in the process, for $c = 1, \ldots, m$;
- P_d represents the measures of pressure along the process, for $d = 1, \ldots, n$;
- G_e are geometric values in consideration, for $e = 1, \ldots, r$.

The bounds l_a, l_b, l_c, l_d, l_e are the lower bounds for the variables and u_a, u_b, u_c, u_d, u_e are their upper bounds.

The amount of scrap (S) depends on all the variables in Table 2, thus:

$$\begin{aligned} S \;=\; & \beta_0 + \beta_1 f_1(T_1) + \ldots + \beta_k f_k(T_k) \\ & + \beta_{k+1} f_{k+1}(t_1) + \ldots + \beta_{k+p} f_{k+p}(t_p) \\ & + \beta_{k+p+1} f_{k++1}(S_1) + \ldots + \beta_{k+p+m} f_{k+p+m}(S_m) \\ & + \beta_{k+p+m+1} f_{k+p+m+1}(P_1) + \ldots + \beta_{k+p+m+n} f_{k+p+m+n}(P_n) \\ & + \beta_{k+p+m+n+1} f_{k+p+m+n+1}(G_1) + \ldots + \beta_q f_q(G_r) + \varepsilon, \end{aligned} \tag{1}$$

i.e.,

$$S = \beta_0 + \sum_{i=1}^{q} \beta_i f_i(x_i) + \varepsilon, \tag{2}$$

with $\varepsilon > 0$, and x_i, $i = 1, \ldots, q$, with $q = k + p + m + n + r$, represents all the variables considered. Also β_0 is the constant and $\beta_i, i = 1, \ldots, q$ are the weights of each variable in the model. While f_i are functions which model the association between each variable x_i and the amount of scrap S. Furthermore, all variables are bounded, and l_i and u_i are the lower and upper bounds of each variable x_i, $i = 1, \ldots, q$.

Therefore, since the goal is the reduction of the amount of scrap, the optimization problem to be solved, can be formulated as:

$$\begin{array}{cc} \min\limits_{x \in R^q} & S(x) \\ s.t. & l_i \leq x_i \leq u_i. \end{array} \tag{3}$$

The optimization problem defined in equation 3, may be linear, if the functions f_i are linear functions, or nonlinear problem, otherwise. In both cases it is an optimization problem with simple bounds.

There are several optimization algorithms to solve this problem, depending on the type of problem considered, i.e.: linear, nonlinear, with a global optimum or with several local optimums, with different size, depending on the number of variables considered.

If it is assumed that all the functions f_i, $i = 1, \ldots, q$, are linear functions. i.e. if it is considered the existence of a linear variation of f, $S(x)$ is a linear model. This model has the amount of scrap as dependent variable and the variables concerned to factors for scrap productions (temperature, time, speed, pressure and geometry) as independent. In the next section, this will be considered. Therefore minimizing S will be possible since the maximum and minimum values of the variables are known. Thus, for obtaining minimum scrap it is necessary to minimize the variables with a positive effect on S and maximize the value the opposite.

3 Empirical Study

In a first study [15], the data on continuous aluminum production of the various profiles for the six months of production a were provided by the company. The stepwise method was used to estimate the linear scrap model, considering the extrusion variables. This method considered all significant variables for a significance level of 5%. This model has an adjusted R square of approximately 46%, therefore the expected percentage of total variability in scrap production explained by the independent variables included in the linear regression model is 46%.

For the accomplishment of the present empirical study, it was used the same database used in the previous work [15], however, all phases of the aluminum extrusion process are now addressed.

Data for comparative analysis was standardized, however, the regression excluded one more variable and did not improve the R square of linear regression. No advantages were observed when considering data from the original study related to the pre-extrusion and post-extrusion phase.

The database includes 42 821 observations, corresponding each observation to an extruded billet. The database contains 65 variables, of which 62 are quantitative (some discrete and other continuous) and three qualitative (nominal). Depending on the phase of the process, the variables considered in this study can be divided into three categories: Pre-extrusion (PR), Extrusion (E) and Post-extrusion (PO) (see Table 3).

Similar to [15], the variables PR_W_B, Weight Billet (kg), and PO_W_B, Bars Weight (kg), are used to define the variable SC_{KG}, the scrap (kg), i.e:

$$SC_{KG} = PR\_W_B - PO\_W_B \tag{4}$$

Dimensions	**Variables**
Temperature	E_T_{CP}: Post Container Temperature (C); E_T_{End}: Max End Temperature (C); $PR\_T_{Z1,Set}$: Set Temperature Z1; PR_T_{BC}: Billet Conical Temperature
Time	E_t_s: Speed Time (s); E_t_D: Dead Time (s); E_t: Extrusion Time (s)
Speed	E_S_C: Extrusion Speed (mm/s); PO_S_p: Puller Speed (m/min); PO_L_p: Pull Length (m); PO_T_{rpDx}: DX Puller Traction
Pressure	E_p_{SL}: Sealing Pressure (bar); E_p_{Max}: Maximum Extrusion Pressure (bar)
Geometry	E_L_B: Billet Lenght (mm); E_L_{Butt}: Butt Lenght (mm); E_NH: Number of Holes; E_SW: Specific Weight; PR_NB: Number of Billets; PO_LB: Bars Lenght (mm); PO_NB: Number of Bars (mm); PO_SS: Saw Speed (%)

Table 3: Description of the variables included in the linear model

Optimizing the overall extrusion process, as well as predicting the behaviour of aluminum at all stages (before, during and after extrusion), allows to anticipate some key variable control issues and consequently improve the extrusion process.

The aim is to determine the most appropriate extrusion variables values in order to minimize scrap production, and consequently avoid excessive costs and promote environmental sustainability. If a linear model to approximate S is considered, problem (3) is classified as simple bounds linear minimization problem.

From the large database on the company's six-month production, it was possible to extract the limits for the variables which are presented in Table 4.

However, if any of the the functions involved in problem (3) is not a linear function, this is a nonlinear problem and thus other methods, appropriate to the type of problem, are required .

To estimate the model of S using the stepwise method, the software IBM SPSS Statistics 25 was used. The results showed that, for a 5% significance level, all variables are significant. The obtained model has an adjusted R square of approximately 53%. Therefore, 53% of total variability in scrap production is explained by the independent variables included in the linear regression model.

Variables	Min	Med	Mean	Std	Max
E_NH	0	2	2.49	1.65	12
E_SW	0	0.77	1.55	1.96	78.42
E_SC	0.44	4.58	4.65	1.41	12.83
E_tS	0	39	42.06	23.09	452
E_t	56	167	173.93	49.09	1200
E_t_D	12	17	18.66	3.62	33
PO_LP	0	43.93	43.62	8.65	58.19
PR_NB	1	13	29.78	43.35	329
E_LB	650	865	850.98	94.41	1113
E_L_{Butt}	12	22	23.62	4.47	150
PO_LB	2050	6500	6542.21	1550.18	12050
PO_NB	0	14	17.24	17.19	228
PO_S_p	0	14.33	13.74	5.43	31.81
PR_T_{BC}	67	445	535.95	266.60	1372
$PR\_T_{Z1,Set}$	40	460	457.83	17.33	510
E_T_{End}	350	565	557.98	27.99	600
$PO\_Tr_{p,DX}$	15	33	33.17	4	78
PO_T_{CH}	10	70	63.85	14.74	95
E_p_{Max}	133	240	236.47	18.43	275
E_pSL	239	247	246.79	1.06	282
E_T_{CP}	407	435	435.43	4.06	451

Table 4: Descriptive statistics of the variables considered in the model (3)

The model can be written as:

$$\begin{aligned} SC_{KG} = {} & 60.447 + 1.097E\_t_D - 0.620PO\_S_p + 0.146PO\_SS \\ & -0.063PR\_T_{Z1,Set} + 1.110E\_SW - 0.001PO\_LB \\ & +0.141E\_L_{Butt} + 1.442E\_NH - 0.028E\_p_{Max} - 0.105PO\_NB \\ & +0.010E\_t - 0.117E\_T_{CP} - 0.121PO\_Tr_{p,DX} - 0.012E\_tS \\ & +0.032PO\_LP + 0.003E\_LB - 0.216E\_SC + 0.004PR\_NB \\ & -0.004E\_T_{End} + 0.061E\_p_{SL} \end{aligned} \tag{5}$$

The analysis of the coefficients of the model (5), which are depicted in Table 5, allowed to conclude that all variables are significant to explain scrap the production of each billet. However, although all variables are significant, some are more important to the model than others.

The analysis of the standard regression coefficients shows that variables E_NH: Number of Holes, E_S_C: Extrusion Speed (mm/s), E_SW: Specific Weight, E_p_{SL}: Sealing Pressure (bar), PO_S_p: Puller Speed (m/min), E_t_D: Dead Time (s), PO_T_{rpDx}: DX Puller Traction and E_T_{CP}: Post Container Temp (°C), are those that have the greatest relative contribution to explain the dependent variable.

In fact, the variables with positive coefficients, and therefore the ones that most influence scrap production are E_NH, E_SW, E_p_{SL} and E_t_D. The results indicate lower scrap production in the process to lower values.

On the other hand, the variables E_S_C, PO_S_p, PO_T_{rpDx} and E_T_{CP} are those that negatively influence scrap production, because the higher values show lower scrap production.

	Unst Coef	Std Coef	St Coef error	t	Sig.	Collinearity Stat	
						Tolerance	VIF
(Constant)	60.447	8.033		7.524	0.000		
E_t_D	1.097	0.01	0.428	112.873	0.000	0.763	1.31
PO_S_p	-0.62	0.014	-0.363	-45.526	0.000	0.173	5.788
PO_SS	0.146	0.003	0.231	45.017	0.000	0.415	2.41
$PR\_T_{Z1,Set}$	-0.063	0.002	-0.117	-25.224	0.000	0.511	1.958
E_SW	1.11	0.035	0.234	31.707	0.000	0.201	4.98
PO_LB	-0.001	0.000	-0.115	-24.923	0.000	0.513	1,95
E_L_{Butt}	0.141	0.008	0.068	18.755	0.000	0.842	1.188
E_NH	1.442	0.049	0.257	29.181	0.000	0.141	7.069
E_p_{Max}	-0.028	0.003	-0.055	-10.8	0.000	0.423	2.362
PO_NB	-0.105	0.005	-0.194	-21.861	0.000	0.14	7.156
E_t	0.01	0.001	0.052	7.677	0.000	0.237	4.226
E_T_{CP}	-0.117	0.009	-0.051	-12.523	0.000	0.662	1.511
$PO\_Tr_{p,DX}$	-0.121	0.01	-0.052	-11.642	0.000	0.544	1.837
E_tS	-0.012	0.002	-0.031	-7.842	0.000	0.722	1.386
PO_LP	0.032	0.005	0.03	6.642	0.000	0.538	1.86
E_LB	0.003	0.000	0.033	6.839	0.000	0.475	2.104
E_SC	-0.216	0.041	-0.033	-5.267	0.000	0.283	3.537
PR_NB	0.004	0.001	0.019	4.901	0.000	0.713	1.403
E_T_{End}	-0.004	0.001	-0.014	-3.713	0.000	0.829	1.207
E_p_{SL}	0.061	0.029	0.007	2.114	0.035	0.989	1.012

Table 5: Coefficients and Collinearity Diagnosis

The model expressed in equation 5 is in agreement with the results previously found by the authors presented in Table 1, since the variables that tend to contribute more to the scrap production during the aluminum extrusion process are the same.

The linear regression approach also assumes that the residuals are independent and identical distributed, with a zero mean, normal distribution and constant variance. These assumptions are generally verified.

For large samples, the Kolmorogov-Smirnov (K-S) or Shapiro-Wilk (SW) normality tests implies the rejection of the normal distribution. In this case, the sample size is large, so therefore, the central limit theorem can be used [11]. The large the sample, the closer to a normal distribution the distribution of the means will be. Consequently the residuals of the model can be considered approximately normally distributed.

For the assumption of the independence of residuals, the Durbin-Watson (DW) Statistics can be considered. Since this test yield the value 0.91 (approximate to 1), it is expectable that the residuals are correlated. This is a limitation of the model and 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 [28].

The values of tolerance are closer to 0 and Variance Inflation Factor (VIF) are smaller than 15, for each independent variable (see Table 5), therefore that there is statistical evidence to support the inexistence of multicollinearity.

In this way, it is possible to obtain an optimal linear model. Using the descriptive analysis of the variables Table 4 and by identifying the maximum and minimum values of each variable, the amount of scrap produced is minized. The maximum value of the variables with positive coefficients and the minimum value of the variables with negative coefficients should considered so that aluminium production achieves the lowest scrap production, which in turns will avoid aluminium recycling.

For further analysis, recognizing the company's interest in sustainable production, the data was standardized and linear regressions were used to model the nine most frequent profiles observed in in total production dataset and also for the nine profiles with an average of more than 20 kg of scrap and frequencies exceeding 100 (see Table 6 and Table 7).

These linear regressions indicate that, as expected, the most frequently produced profiles lead to the lowest amount of billet-produced scrap and the less frequently produced profiles have more billet-produced scrap. This is an indicator of the stability throughout the production process.

The results presented in Table 6 and in Table 7 show the scrap quantity models (SC_{KG}: Scrap (kg), dependent variable) of the 18 selected profiles (9 most frequent profiles and 9 profiles with more than 20 kg of scrap). From these tables results, the die and the number of holes in the die (Number of Holes: E_NH) are similar, i.e., these are variables without great variability. However, it is well known from literature that die geometry, as well as the components used, are causes of the amount of scrap produced in a profile [4, 20, 40, 51]. Arif [4], concluded that geometry is a parameter that should be well adjusted for each alloy type. Hatzenbichler [20], points out that die geometry is the main cause of defects in profiles. In this sense, the work developed by Vaneker [51] presents rules for the development of matrices, considering matrices design extremely important in the production of the quality profile. The work developed by Qamar [40] considers that defects in dies and tools are the main source of profile defects and, consequently, scrap production. ADLA has developed several quality control systems, in this area in particular three-dimensional analysis of aluminium profiles [2].

The coefficients of the linear models, presented in Table 6 and in Table 7, are able to identify the variables that most contribute to scrap production. The missing coefficients correspond to non-significant variables for the model.

The analysis of the most frequently produced profiles, whose results are presented in Table 6, linear models were obtained for which the geometric

	A	B	C	D	E	F	G	H	I
(Constant)	-34.924	-1.5	-25.761	-8.202	-24.239	-51.198	-40.935	3.766	-8.292
E_t_D						0.002		0.01	
PO_S_p	0.114	0.671	-0.013	-0.267	-0.471	-0.094	0.305	-0.007	
PO_SS	-0.071			0.022	0.089		0.031		
PO_B/P		0.187	0.313			-0.003			
$PR\_T_{Z1,Set}$					0.091				
PO_LB	-1.546	-0.721	-2.38	-1.309	-2.191	-2.51	-1.414	-1.439	-1.314
E_L_{Butt}	-0.077	0.038			0.042		0.026	0.007	-0.005
E_SW	-0.058	-2.163	-42.973	-10.639	-5.097	0.06	0.201		-14.299
E_t		0.228		-0.236	-0.251	-0.047	0.061		
E_NH	10.07	1.098							
PO_NB	-52.309	-1.537	-2.603	-12.56	-34.033	-63.315	-50.194	-2.756	-10.024
E_T_{CP}						-0.002			
E_p_{Max}	0.046				-0.066	-0.007	0.013	0.038	
$PO\_Tr_{p,DX}$	-0.038	0.067		-0.059	0.097			0.016	
E_tS	-0.016	0.027	0.007	0.023				-0.01	-0.019
E_LB	1.142		0.932	0.875	1.099	0.896	0.798	0.828	0.925
E_SC		-0.251		-0.018	-0.076	-0.006			
PR_NB	-0.017	-0.049	-0.016	-0.013			-0.01	-0.006	
E_T_{End}		0.023	0.031		-0.147				
PO_LP	-0.064	0.024		-0.033	0.035				
$E\_PR_{T_{BC}}$	-0.006	-0.012				0.01			
E_p_{SL}				-0.016	0.075		-0.02		-0.004
Frequency	2596	1331	1194	980	906	894	842	723	697
Scrap (KG)	11.415	9.627	6.801	8.159	10.594	11.294	10.461	8.485	8.81
R_a^2	0.804	0.606	0.96	0.966	0.925	0.996	0.962	0.998	0.986

Table 6: Linear Regressions Standardized of the Most Frequent Profiles

variables present significant coefficients, regardless of the matrices. These results reinforce the effect of geometric factors on the amount of scrap produced. It may be concluded that in addition to the die geometry and tools mentioned [4, 20, 40, 51], there are other geometric factors that can contribute significantly to scrap production.

In particular, it can be seen that Length Bars (PO_LB) negatively contribute to scrap production, for all most frequent dies. Therefore whenever this length is reduced, scrap production increases. Similar behavior can be observed for the Number of Bars (PO_NB) and the Number of Billets (PR_NB). The opposite behavior is observed for the Billet Length variable (E_L_B). Billet Length contributes for scrap positively, meaning that its increase implies an increase in scrap production.

In some profiles, the geometric variables Butt Length (E_L_{Butt}) and Specific Weight (E_SW), contribute positively to the increase in scrap production (since which has a corresponding positive coefficient), while in others have the opposite contribution.

The lack of studies in literature on billet length do not allow a critical analysis. However, further analysis is required. This unexpected result may come from alloy type [4] or from previous billet size calculations due to customer specifications.

	J	K	L	M	N	O	P	Q	R
(Constant)	-45.593	1.274	-49.869	-28.252	3.308	1.952	1.621	3.083	-2.039
E_t_D									-0.028
PO_S_p		0.102	-2.42			-0.121	-0.109		
PO_SS	-0.011			-0.102			0.346		
PO_B/P									
$PR\_T_{Z1,Set}$			0.648						0.036
PO_LB	-1.254					-1.14	-0.56	-1.672	-0.312
E_L_{Butt}	-0.013	0.018	-2.180	0.012	0.093	0.032	0.015		0.054
E_SW	-71.739	-0.613	-3.702	-45.268	-1.191	-2.732	0.578		
E_t	-0.022	0.051	-1.472		0.05				0.098
E_NH	-0.367								1.716
PO_NB	-1.531	-5.427	-72.07	-0.669	-0.679	-1.363	-2.193	-2.312	-0.234
E_T_{CP}			0.026	-0.041	0.021				0.035
E_p_{Max}	-0.015					-0.068		0.009	0.078
$PO\_Tr_{p,DX}$				-0.033		0.033		0.016	
E_tS		0.039							0.07
E_LB	1.015	0.526	1.152	0.654	0.512	0.942	0.728	0.86	0.096
E_SC	0.033		-0.047			0.081			
PR_NB					0.041		-0.038		
E_T_{End}	-0.071	-0.093	0.063	0.043		0.246		-0.037	
PO_LP					0.876	-0.074	-0.417		
$E\_PR_{T_{BC}}$	-0.017			0.044					
E_p_{SL}	0.021			0.004	0.037		0.02		
Frequency	154	182	227	188	141	301	274	135	107
Scrap (KG)	43.55	43.518	43.236	41.574	35.273	25.476	23.291	22.147	20.4
R^2_a	0.986	0.983	0.993	0.951	0.975	0.995	0.999	1	0.999

Table 7: Linear Regressions Standardized of Profiles With Higher Scrap

Regarding temperature, for the four variables considered: Post Container Temp (°C) (E_T_{CP}), Max End Temperature (°C) (E_T_{End}), Set Temperature Z1 ($PR\_T_{Z1,Set}$) and Billet Conical Temperature (PR_T_{BC}), almost no effect on scrap production was observed. Similar behavior was obtained for the variables time, speed and pressure. Despite these results, it cannot be concluded that temperature, speed and pressure do not influence the amount of scrap produced. Although data show no evidence that these parameters influenced scrap production for the studied profiles. These effects are well documented in the literature, as presented in Table 1. In general, increasing temperature and pressure increases the amount of scrap, while time and speed are directly related to previous variables. On the other hand, all dependent variables depend on the alloy type used to produce a specific profile [4]. The company's empirical knowledge of the influence of temperature, pressure, time and speed on the amount of scrap produced by the experience led to the company's growing concern and greater employee control over these parameters during the production process.

In the Table 7, are presented models for profiles with the largest amount of scrap produced in the company. For each significant linear models were obtained. The geometric variables Butt Length (E_L_{Butt}) and Specific Weight

(E_SW) again show a significant contribution to the scrap production, which reinforce the results presented in Table 6. For example, the Length Bars (PO_LB)) contribute negatively to scrap production. Generically, similar behavior can be observed for Specific Weight (E_SW) and Number of Bars (PO_NB). As mentioned in the previous analysis, the variables related to the geometric factors have significant coefficients for all matrices, which means a great influence on scrap production.

Regarding the other variables, it is also verified that the main variables associated with the extrusion process do not influence the amount of scrap produced, during the extrusion process for the analyzed profiles, namely extrusion time, velocity and pressure.

In summary, according to this study, to improve production by minimizing scrap production in the company, better control of geometry variables is necessary. However, these variables are not easy to control because they are very dependent on customer orders. Perhaps the company can exercise greater control in the production, inspection and correction of the matrices.

Thus, the identified gaps can serve as an important basis for improving the company's aluminum extrusion process, as the geometric factors identified have been little explored in literature.

4 Conclusions

The literature review performed in this work allowed to gather some consensus opinions on the role of sustainability in the manufacturing industry [36, 48]. In fact, the strong relationship of dependence between the different extrusion variables was evident (c.f. Table 1).

Considering the real data at from a Portuguese company in the aluminium extrusion sector, the results show that variables concerning extrusion temperature, time, speed, pressure and die geometry are crucial to improve and control the scrap production. It is concluded, after analyzing the linear regression models, that the most prominent factors for waste in this company are the geometric ones. However, the results may vary from company to company depending on their size and the amount of profiles produced and sold, and also on the knowledge of the process and variables control capacity.

The indicators obtained in this analysis allow the evaluation of the main variables that contribute to the production of large quantities of scrap. According to this study, to improve the company's production, i.e. minimizing scrap production, it is necessary to control all independent variables. The analysis of the coefficients of the developed model, allow to conclude that, all variables, except PR_T_{BC}, are significant to explain scrap production in the extrusion process of each billet. In the model the variables E_NH, E_SW, E_p_{SL} and E_t_D present a positive influence in scrap production, meaning that these decrease implies a smaller production of scrap. In opposite, the increase of the variables E_S_C, PO_S_p, PO_T_{rpDx} and E_T_{CP} implies the reduction of the amount of scrap produced. This systematization of evidence helps the company under study to produce more quantities of profiles with less waste, protecting the environment through minimizing the environmental impacts of its activity.

Achieving sustainable competitive advantages depends on the strategic planning formulated and implemented by the company. In this particular case, this plan in production is evident, because the extrusion variables, point in literature as crucial, in our model were not found to be the most important. To the extent that the results indicate that extrusion variables appear to be well controlled by the company throughout the process.

Thus, according with our study to improve production, minimizing the scrap production in the company, a better control of the geometry variables is necessary, when possible, because these are differentiating, when we considered the scrap production effect. However, these variables are not easy to control, because are very dependent of the clients orders. Perhaps the company can exert greater control in the production, and on inspection and correction of the dies. That way, the identified gaps serve as an important basis for improving the company's aluminum extrusion process. Geometric factors, often associated with dies and repair operations, which generate unwanted product defects have not been reported in detail in the published literature.

It is desirable that this company, as well as all companies in the industrial sector, aim to be competitive, modern but simultaneously responsible and guaranteeing the future of future generations, reducing the need for primary material inputs. A sign of this is that many companies are embracing the environmental challenge by implementing incremental changes in their production systems [36]. There are many technological parameters that influence it [33], technology and innovation are important factors in achieving sustainability goals [36].

One possible future work is to study the use of nonlinear functions for modeling the relationships between variables. Another hypothesis is to study in deep the geometry of the matrices, since, from the analysis of the models, the most important factors are the geometrical ones.

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Chapter 4

Conclusion and Future Research

The aluminum extrusion process in a Portuguese company, and the variables involved in the whole process were studied in this work. An usual problematic in the metallurgical sector, the scrap, was approached using optimization and statistical modeling. Through multiple linear regressions was estimated the amount of scrap, depending on a set of extrusion conditions. This project is based in the productive process of ADLA Aluminium Extrusion S.A.

Aluminum extrusion is the main industrial process used to create profiles of a fixed cross section. Allowed optimizing the amount of raw material consumed and the quality of the extruded product, further ensures the company's suitability, the energy save and customer specifications.

In this last chapter, the main conclusions and suggestions on the approaches developed and decision support suggestions are compiled. During the period of execution of this work some future works and limitations were also identified, promising research guidelines.

It was possible to observe an evident relation between the variables considered in the process and the amount of scrap in the extrusion process.

To achieve the reduction of scrap in company's process two studies were performed. In both, multiple linear regressions [7] are considered, with the dependent variable the amount of scrap in the aluminium extrusion process and with independent variables the various variables involved in the process. In the first study only extrusion variables are considered, while in second pre-extrusion, extrusion and post-extrusion phases have been taken into account. Thus, it was possible to identify the level of importance of the variables under study for the scrap.

The strong relationship of dependence between the different extrusion variables was evident, according with literature review in Chapter 2 and 3.

Throughout the first paper of this work, the review allowed to gather some consensus on the role of the extrusion variables in scrap in the manufacturing industry [12, 17]. Based on that literature review five research hypotheses, that relates the amount (kg) of scrap, in the production of each billet (as dependent variable), with the various (independent) variables, were formulated. The results show that variables concerning with extrusion temperature, time, ram speed, pressure and die geometry are crucial to improve and control the scrap. In particular, the amount of scrap is higher with the increase of the E_t_D: Dead Time (s), E_t: Extrusion Time (s), E_t_s: Speed Time (s), E_p_{SL}: Sealing Pressure (bar), E_L_B: Billet Length (mm), E_L_{Butt}: Butt Length (mm), E_NH: Number of Holes, E_SW: Specific Weigh. The amount of scrap is greater with the increase of the E_T_{CP}: Post Container Temperature (°C), E_T_{End}: Max End Temperature (°C), E_S_C: Extrusion Speed (mm/s) and E_p_{Max}: Maximum Extrusion Pressure (bar).

In turn, the second study has also five dimensions, according to the literature review, and by analogy to the previous study, although considering pre-extrusion, extrusion and post-extrusion variables. Considering the actual data from a Portuguese company in the aluminium extrusion sector, the results show that variables concerning extrusion temperature, time, speed, pressure and die geometry are crucial to improve and control the scrap. The analysis of the coefficients of the model, let to conclude that, all variables, except PR_T_{BC}: Billet Conical Temperature, are significant to explain scrap in the extrusion process of each billet. In the model the variables E_NH: Number of Holes, E_SW: Specific Weigh, E_p_{SL}: Sealing Pressure (bar) and E_t_D: Dead Time (s) shows a positive influence in scrap, meaning that these decrease implies a smaller production of scrap. In opposite, the increase of the variables E_S_C: Extrusion Speed (mm/s), PO_S_p: Puller Speed (m/min), PO_T_{rpDx}: DX Puller Traction and E_T_{CP}: Post Container Temperature (°C) implies the reduction of the amount of scrap.

In summary it is known that to improve the company's production and profit, it is necessary to control all independent variables in the model, minimizing scrap. Thus, after analyzing the linear regression models, which studied profiles, it was observed that the most prominent factors for waste in this company are the geometric ones. This results suggests that the other variables in the process are well monitored and controlled by the company employees.

However, that results may vary from company to company, depending on their size and the amount of profiles that they produce and sale, and also the knowledge of the process and their variables control capacity.

Knowing the effect of the most important variables in the process, presented in this work, will allow the company under study to produce more quantities of profiles with less waste, thus protecting the environment and minimizing the negative impacts of its activity.

In the case of geometry variables, they are not easy to control, because they are very dependent on customer orders. Thus, it is important for the production line staff to have knowledge of each extruded profile, as presented in this work, for they react according to the profile and tool they are using.

A greater control in the production, inspection and correction of the dies, can be suggested. That way, the identified gaps serve as an important basis for improving the company's aluminum extrusion process. Geometric factors, often associated with dies and repair operations, which generate unwanted product defects have not been reported in detail in the published literature and may be a future direction in this investigation.

The importance of the monitoring capacity is an asset of the company and creates a great potential for continuous improvement. The monitoring and control of variables allows to suggest and implement corrective and preventive actions, that is, allows to support correct decisions.

Thus, it is desirable that this company and all companies in the industrial sector aim to be competitive, modern but simultaneously responsible and concerned in guaranteeing the future of future generations, reducing the need for primary material inputs. A sign of this is that many companies are embracing the environmental challenge by implementing incremental changes in their production systems [12]. There are many technological parameters that influence it [11], technology and innovation are important factors in achieving sustainability goals [12].

This work allows to point several possibilities for future work. An opportunity for future research is to study nonlinear functions for modeling the relationships between variables. Another hypothesis is to study in deep the geometry of the matrices, since, from the analysis performed in this work, the most important factors, with higher statistical significance, are the geometrical ones. Another possibility is grouping the independent variables using factor analysis and performing a linear regression of the factors obtained, with this methodology can also be a possibility to improve the analysis. To limit the number of variables considered in the model can would be a possibility to be tested. It would also be interesting to validate the model estimated with data not in the training test, that is, data after July, 2018, once in this work all data are used to estimation, and a test set is not considered. Alternative artificial intelligence techniques could also be good tools to improve the performance and accuracy of the proposed analysis.

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