



ALGARVE UNIVERSITY
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***The optimization of the milling process in the Portuguese Moulds Industry and
its contribution to the sustainability of the company and of the environment***

Filipe André da Silva Narciso

Dissertation

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Susana Cristina Serrano Fernandes Rodrigues, PhD

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*The optimization of the milling process in the Portuguese Moulds Industry and
its contribution to the sustainability of the company and of the environment*

I declare that I am the author of this work, which is original and unpublished. The authors and works consulted are cited appropriately in the text and included in the list of references.

(Filipe Narciso)

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“We must all learn to live as brothers or we will all die like crazy.”

Martin Luther King

To all who support and respect me
and give meaning to my life.

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ABSTRACT

The aim of this research is to optimize the production process during the milling stage in the Portuguese Moulds Industry (PMI) for plastic injection, through the use of a new form of milling (increased lateral and axial increment of the tool) that contributes to the sustainability of the company (energy saving, machine-saving hours) and to reducing their environmental impact (reduction of carbon dioxide emissions). Thus, the adoption of a new milling strategy will contribute to the company's competitiveness through the optimized use of energy resources and skilled labour, as well as reducing carbon dioxide emissions (CO₂).

During the study, secondary information was analyzed in order to contextualize and understand the PMI, in particular one of the stages of its production process – milling. In this way, the study took place in a company situated in Marinha Grande (Portugal) and focuses on the moulds produced by the same company in 2010. From a stratified random probability sample, justified by the tonnage diversity of the moulds and by the representativeness of the results, simulations of two milling strategies were carried out (a commonly used – conventional – and proposed – sustainable) in order to measure the times resulting from simulations. Thus, from the obtained results the comparative analysis of figures relative to the man-machine hours, the energy consumption and carbon dioxide emissions (CO₂) was possible.

The results, obtained from the measurement of time relative to the two milling simulations (conventional and sustainable), show a significant reduction in simulation times (more than 2 months of useful work) when opting for sustainable milling, which is reflected in the man-machine hours required, energy consumption and carbon dioxide emissions (CO₂). Moreover, these immediate gains are accompanied by the possibility of meeting the deadlines stipulated by clients, producing more moulds with the same resources and reducing the environmental impact, increasing the company's competitiveness and improving its image among stakeholders. Thus, the optimization of the milling process and the consequent reduction in time used, is important for the economic use of resources and energy, contributing to the competitive potential of the company and its environmental sustainability.

Keywords: milling; optimization of the production process; moulds industry; sustainability.

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Abbreviations

ae – radial increment (lateral)

AICEP – Agency for Investment and Foreign Trade of Portugal

ap – axial increment (in level Z)

CAD – Computer Aided Design

CAE – Computer Assisted Engineering

CAM – Computer Aided Manufacturing

CEFAMOL – Portuguese Association for the Mould Industry

CNC – Computer Numeric Control

CO₂ – Carbon Dioxide

EDP – Energies of Portugal

USA – United States of America

FEIS – Stephens Brothers Factory School

fz – speed per tooth

PMI – Portuguese Moulds Industry

ktep – kilo ton of oil equivalent

mm – milimeter

mm/min – unity of tool speed (milimitres per minute)

NC – Numeric Control

UN – United Nations

SME – Small and Medium Business

IS – International System

Ton – tonne

TÜV – Technischer Überwachungs-Verein

CV – Control Variable

DV – Dependent Variable

EV – External or Parasite Variable

IV – Independent Variable

MV – Moderating variable

WBCSD – World Business Council for Sustainable Development

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PART I

The first part is constituted by the introduction, justification of the relevance of the topic, presentation of the research problem, characterization of the PMI and the literature review. Thus, it contextualizes the optimization of the production process in PMI from a sustainable perspective which contributes, on the one hand, to the company becoming more competitive (reducing the use of skilled labour and energy) and, on the other hand, contributes to preserving the environment for future generations (with the decrease of energy consumption and the consequent reduction in emissions of carbon dioxide (CO₂) to the atmosphere). Finally, the hypotheses to test and outline – the research model were defined.

1 Introduction

This thesis aims to contribute to the optimization of the production process in the Portuguese Moulds Industry (PMI) for plastic injection by reducing the milling time in machining the adjustment areas of cavities and cores. It is important to note that milling is critical in the manufacturing process of the mould, because this is the most economical method of material removal in defining the piece geometry. In this way, most of the pieces pass through this section, so it is considered the "heart" of the production process of the moulds industry.

In this context, a process of innovative/sustainable¹ milling when compared to the commonly used/conventional² milling will be presented and the results obtained by simulation will be analysed.

In the sector of the moulds, the optimization of the production process is a particularly relevant theme because rethinking the production process not only increases the competitiveness of enterprises through efficient processes, but also contributes to the protection of the environment, from a sustainable perspective. Concerns about the environmental impact of the activity contribute to the sustainability of the company, as it enables costs to be lowered and their relationship with the market to be improved.

¹ **Sustainable milling**, means the alternative proposed in this study which implies the differentiation of finishes in the moulding area and in the adjustment zone. In this type of milling, the increment axial and/or radial depending on the finishing operation will increase.

² **Conventional milling**, means the one that currently takes place and which is characterized by the same type of machining in the finishing area and in the adjustment zone.

This research focuses on the analysis of different machining strategies (conventional and sustainable) and the measurement of their times through simulation. It is intended to determine whether the cutting parameters influence the time of production of moulds with different tonnages and to verify that the proposed machining strategy, known as sustainable, reduces the company's costs and its environmental impact. It is intended, through a process of simulation in software (used on a daily basis in the company to create programs), to measure the direct effects of machining strategies simulated in the productive times, and the indirect ones in the man-machine hours, in the energy consumption and in the environment.

This study is divided into 3 parts. The first consists of the introduction, justification of the relevance of the topic, presentation of the research problem, the characterization of the PMI and the literature review. Thus, it contextualizes the optimization of the production process of PMI from a sustainable perspective that contributes, on the one hand, to the company becoming more competitive (reducing the use of skilled labour and energy) and, secondly, it contributes to preserving the environment for future generations (with the decrease of energy consumption and consequent reduction in emissions of carbon dioxide (CO₂) to the atmosphere). Finally, the hypotheses to test and outline the research model were defined.

In the second part, the construction process of the research in all its different stages is explained: the collection of information, type of research chosen, the intended population, sample construction, characterization of the company where the study was conducted, the variables and experimental and control groups, gathering and defining the cutting parameters, the model computer simulation, the software used and, finally, the internal and external validity of the study.

In the third part, the results relating to the time differences between conventional and sustainable simulations (the simulation proposed in this dissertation) regarding the process of milling and resources (human, energetic and environmental) will be analysed and discussed and the implications for academic knowledge and management will be discussed. The limitations of the study and suggestions for future studies will also be set out.

2 Arguments supporting the relevance of the theme

Traditionally, economic development and environmental protection appear as irreconcilable elements. However, it is impossible not to overlook the fact that, firstly, the planet has a limited capacity as a provider of resources and, secondly, the population growth and the changing of consumption patterns, have led to the need for increased production (Ferreira, 2010). According to Savitz (2007) and the *World Business Council for Sustainable Development* (WBCSD, 2010)³, in 2050, with the world population approaching 9 billion, the resources of five planets like Earth will be required for the people of China, India and Africa to consume resources with the same intensity as Americans do today.

The UN (2011a) warned about the importance of the scarcity of resources, considering that this is the greatest challenge of the industrial sector, since the scarcity of resources is reflected in the costs of raw materials and energy used during the production process. What is proposed in this work is the optimization of the production process in the milling sector in the Portuguese Moulds Industry (PMI), because companies that make the best use of resources, improving their production processes, will be more efficient and competitive and, of course, more sustainable. In this dissertation, it is intended to show that the change of some procedures adopted may put the Portuguese moulds sector at an advantage, increasing its domestic and international competitiveness. According to Young (2007) and El-Haggar (2007), companies profit from sustainability, which is that the efficiency of processes leads to a more sustainable company and, moreover, improves its relationship with the market. In this context, the materials chosen for the production of a well must be carefully selected, so as to minimize both the waste of raw material and the environmental impacts avoiding emissions of carbon dioxide (CO₂), for example.

This paper focuses on the production process, i.e. the point in time when the transformation of the raw material (steel) in the tool (mould) occurs through the process of milling. Thus a rethinking of the operationalization of the production process is proposed, as suggested by El-Haggar (2007), when constructing the CNC program (simulation tool path⁴), reducing machining times and, therefore, the consumption of

³ in UN, 2011a

⁴ The tool path consists of several radial and axial increments which, as a whole, is designated CNC program.

human resources, energy, consumables, among others, while minimizing the environmental impact. In this study it is intended, at the same time, that the PMI contributes to sustainable development and the optimization of the production process through the adoption of sustainable milling, contributing to the reduction of production costs and the environmental impact of the company, and improving their image and their products (Young, 2007).

3 Problem Research

3.1 Objectives of the study

The objectives defined for this study are:

- to reduce machining times in the moulding zones (cavity and core) in the finishing stages of milling in the mould production process;
- to analyze the relationship between the types of milling and respective times in the finishing stages of the production process of the mould;
- to develop and implement sustainable milling process to save manpower, reduce energy consumption and the emission of carbon dioxide (CO₂);
- to verify if the sustainable milling process lessens the environmental impact;
- to apply this study to moulds with different dimensions (tonnage).

According to Malakooti and Deviprasad (1989) and Hatna, Grieve and Broomhead (1998), the optimization of cutting conditions (milling) should involve the maximization of material removal in the roughing stage, to ensure the desired quality and the predefined tolerance in the machined surface in the stage of completion, thus it will be possible to improve productivity, reduce machining times and increase tool life. In this context, they fall under the objectives defined for this study, since it is intended to reduce the time of milling, to improve economic competitiveness and the company's environmental impact.

3.2 Research Questions

To fulfil the objectives of the research some initial questions were asked:

- Does increasing the increment radial and axial in the machining program contribute to the optimization of the milling process?
- Does increasing the increment radial and axial in the machining program make it possible to obtain better milling times during the finishing phase?
- Can these changes in programming be used in moulds of different dimensions (tonnage)?
- Does using the sustainable milling make it possible to reduce the costs of the production process in companies of PMI?
- Does the use of sustainable milling reduce the environmental impact of the companies of the PMI?

4 The Portuguese Moulds Industry (PMI)

4.1 What is a mould?

A mould is a container prototype that aims to produce an object with a specific shape. Within the area of the moulds there are several classifications depending on the technology used or the raw material to shape. According to the first, moulds can be classified according to the technology of injection, compression, transference, blow moulding, thermoforming and rotational. According to the second, moulds can be classified in thermoplastic, thermoset, rubber, glass and light alloys (Ferreira, 2001).

A simple steel mould (for thermoplastic injection/plastic) consists of two parts: one female (the cavity) and other male (the core) that fit together. Once fitted there is a space with a given and accurate thickness in which the fluid (raw material) is injected to be moulded.

The moulds are manufactured for a variety of industries with different levels of complexity (they can range from automotive to agriculture). However, an individual

mould is no more than a highly personalized tool, serving solely to produce pieces (in small or large series) for which it was designed (Rodrigues, 2002).

Depending on the complexity, the number of pieces to inject and the type of industry it is intended for, among other factors, each mould has different requirements that directly affect the method of construction, delivery time and cost. However, it demands a set of geometric and dimensional conditions, that require skilled and precise equipment (Ferreira, 2001).

4.2 Historical Evolution of the Portuguese Moulds Industry

The origin of the Portuguese Moulds Industry for injecting plastic materials was the creation of the first glass factory in Portugal (in 1719), built by king João V in Coima, Lisbon, Portugal. However, it was only on October 16, 1769, that the “Real Fábrica do Vidro” (Royal Glass Factory), now known as “Fábrica Escola Irmãos Stephens” (FEIS – Stephens Brothers Factory School) (Ferreira, 2001; Rodrigues, 2002), began its activity in Marinha Grande (Portugal), becoming essential in the development of workers' skills that would be later used in the mould industry (Rodrigues, 2002). Indeed, the history of the PMI is closely linked to the Portuguese Glass Industry (Rodrigues, 2002), not only because the second was the precursor of the first, but also because the former produced moulds intended for the glass industry allowing *“the development of a skilled workforce, as well as competences and technical capabilities that were essential for the production of moulds for plastic”* (Rodrigues, 2002:93).

The appearance of the first plastics factory in Portugal (1935) brought a new opportunity for development of the sector that, in addition to serving the glass industry, began to produce moulds for bakelite (an early plastic material used in the production of caps and other simple plastic pieces) (Ferreira, 2001). Anibal H. Abrantes and his brother started the production of moulds for the compressed plastics industry with its first unit (mould) in 1937 (Rodrigues, 2002).

Although World War II (1939-1945) affected the production of moulds for both industrial centres in Portugal (Marinha Grande and Oliveira de Azeméis) (Beira, 2007), it was in 1944 that Anibal H. Abrantes created a company dedicated exclusively to the

production of moulds for the plastics industry, in a precursor of what would be the PMI for plastic (Rodrigues, 2002).

In 1946 a new type of plastic, the thermoplastic, “*which has as its key feature the change of physical and mechanical properties such as temperature*” (Ferreira, 2001) emerged. That same year, Santos & Abrantes, in Oliveira de Azeméis produced the first mould for thermoplastic injection (Cefamol, 1996). This new technique for producing plastic parts revolutionized the market for the production and marketing of plastic parts (Ferreira, 2001) at all levels. The specificity of the sector enabled the specialized training and qualification of employees, who undertook and created their own company, to take place thus contributing to the growth and development of the PMI (Rodrigues, 2002). Currently some of these companies, whose national and international reputation is unquestionable (Rodrigues, 2002) still exist, managed by people who have learned the art of “working the steel“. That is the reason why the company of Anibal H. Abrantes was considered the “university” of the PMI in the sector of moulds for plastic injection (Rodrigues, 2002).

In 1954 the industry underwent another transformation caused by the internationalization of sales. The first countries were the United Kingdom and the United States of America, followed by others worldwide (Rodrigues, 2002). At that time the entire production was exported and this attracted new foreign customers, enhancing the sector's growth again with the emergence of new intermediaries, companies, suppliers, and other agents. The high consumption which was felt in the 50s potentiate the growth of the sector, with Marinha Grande (Leiria) and Oliveira de Azeméis (Aveiro) remaining as strong centres serving several industries: automobile, aerospace, electronics, home appliances and toys (Rodrigues, 2002).

In 1980, the country was exporting to over 50 countries, with 64 companies, employing a total of 2000 people in Marinha Grande and Oliveira de Azeméis (Cefamol, 1996). In 1983, the innovative and visionary company, Aníbal H. Abrantes, “*was the first European company in this sector to install the CAD⁵ / CAM⁶ technology, computerized systems used in project design and production*” (Ferreira, 2001:20). Effectively, Portuguese companies are among the main users of computer assisted technology in the

⁵ CAD – Computer Aided Design

⁶ CAM – Computer Aided Manufacturing

design and manufacture of metal moulds for plastic injection (CAD / CAE⁷ / CAM), which, according to Rodrigues (2002), enables the competitiveness of companies to increase by reducing delivery times and reduced costs, but without jeopardizing the quality of the product.

Since then, all, the PMI has invested heavily in its modernization, in order to be updated both technologically, as in research and development, as Rui Tocha, general manager of Centimfe (Tocha in Jornal Região de Leiria, 2012) stated: *“The industry is doing two things: it is investing in enhancing the current existing capacity and is already positioning itself to enter new supply chains, to enter new technological niches”*.

4.3 Growth and Characterization of the Portuguese Moulds Industry

Data provided by Cefamol (2011) indicate that in 2010, the Portuguese Moulds Industry comprised *“532 companies, with a size of SMEs, dedicated to the conception, development and manufacture of moulds and special tools, with a geographic bipolar distribution between Marinha Grande and Oliveira de Azeméis”* (Cefamol, 2011:2), employing 8250 collaborators to date. However, the subsistence of the sector has not been linear and its growth process reflects this route.

After continued growth in the decades 40-70 (Rodrigues, 2002), the industry reached a peak of growth in the 80s, considered the best ever in the PMI (that which was related to the entry of Portugal in the European Union), since then there has been an exponential increase in the manufacture of moulds, helped by the rapid growth of the international “plastics market“, making it difficult for the PMI to respond to all orders as supply could not satisfy demand (Rodrigues, 2002).

In the 90s the industry started slowing down resulting from increased competition, the economic crisis of the early years and the high interest rates (O Molde n°20 e n°21, 1993). In the 2000s this trend has accentuated, leading to an unprecedented stagnation in the industry (Rodrigues, 2002). It is not a surprise that there was, until 2010, a slight decrease in business creation and employability in the sector which, to date, has been seen as an example of the domestic industry (O Molde n° 89, 2011; Cefamol, 2011).

⁷ CAE – Computer Assisted Engineering

The way the PMI meets the demands of its customers can justify the fact that about 90% of production is for export (see Figure 1), since this sector has staff with expertise and appropriate technology to meet the needs of those who seek the Portuguese Industry, which has enabled it to survive the hardships. According to Vieira (2007:55)

“the success of the national mould industry is due primarily to the following:

- *A very good international image;*
- *High capacity to adapt to technological and market developments;*
- *Sensitivity to innovation and modernization;*
- *High production capacity, using new technologies;*
- *Human resources with strong empirical experience.”*

Vieira (2007) adds that to maintain export levels, the industry will have to strive to use updated technology and the modernization of existing machines,

“Only in that way will the sector be able to answer:

- *The needs of the industry’s customers (increasingly stringent);*
- *The proper management and production planning (to respond to delivery in less time while providing competitive prices);*
- *Monitoring and improving the quality of its products and services (through investment in training, which is essential for the creation of these elements of competitiveness in key international markets)”* (Vieira, 2007:55-56).

The report of the AICEP (Agency for Investment and Foreign Trade of Portugal), published in 2012 (see Table 1), shows that in the period 2005-2009 Portugal remained, on average, in 11th place worldwide, with a mean increase of exports of 3%, which, in global terms is not significant, since, in 2009, China and Japan had results for exports of 13,99% and 11,47%, respectively.

Table 1 – Position and share of Portugal in world exports of the sector

Posição e Quota de Portugal nas Exportações Mundiais do Sector						
	2005	2006	2007	2008	2009	
Posição	12	11	12	10	8	Em 2009, China e Japão foram os principais exportadores mundiais de moldes, com quotas de 13,99% e 11,47%.
Quota (%)	2,94	3,13	2,88	3,29	3,56	

Source: AICEP (2012)

Although in international terms Portugal does not have a clearly expressive position, the PMI is important for the national economy, because the data corresponding to 2011 provided by the Portugal Bank (2012) show that, in general, Portugal had a decrease in exports of 0,9 percentage points 2010 (16%) for 2011 (15,1%). However, in the mould industry, there was an increase in exports of around 15% in 2011 to different countries: Brazil (80%), Poland (50%), France (50%) and Spain (17%) (Jornal Região de Leiria, online edition April 30, 2012), which, as João Faustino, Cefamol president, told the Jornal Região de Leiria (online edition April 30, 2012), is due to “*a gradual return of customers who had relocated to Asia*” and “*who are returning, scared away by the level of quality problems, maintenance costs during the production process and issues of confidentiality agreements*”. It is also important to note that the moulds sector is divided into two geographical areas (Marinha Grande and Oliveira de Azeméis), playing an important role in the local economy and employment levels of those regions, as indicated above, although these declined in 2010 (O Molde n.º 89, 2011; Cefamol, 2011).

In the first decade of this century, there was a decrease in business creation, but as already mentioned, the moulds sector has resisted several adversities of the markets, maintaining an average export of about 90% in the decade from 2000 to 2010 and, according to Cefamol (2011), the trade balance in the moulds sector in the last decade in Portugal, has grown significantly in terms of exports from 234,23 million euros (2000) to 259,2 million euros (2009).

The report of the AICEP (2012) presents the values of the export sector of the PMI in 2006-2010 (see Figure 1). It is observed that the export values are always well above the imports, although this has increased. These data corroborate those presented by Cefamol (2011) for the year 2010, when the PMI would have a production volume of 350 million euros, of which 90% would result in exports, which amounts to 318 million euros.

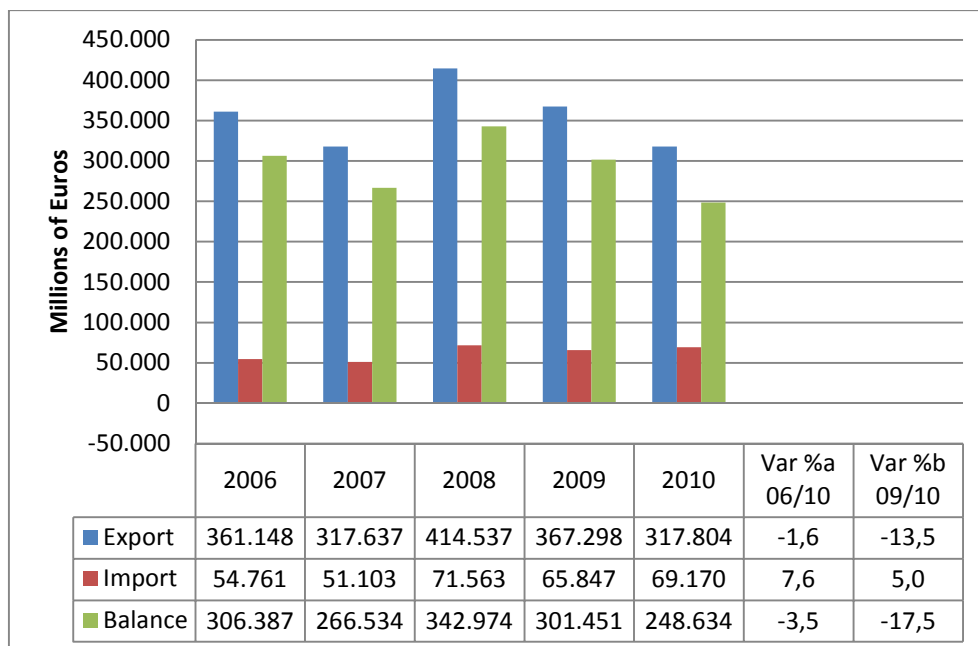


Figure 1 – Trade balance in the sector between 2006-2010

(units - millions of euros)

Source: AICEP (2012)

The predominance of exports (about 90% of national production) (see Table 2) protects the sector in the Portuguese economy, but makes it highly vulnerable to the economic situation of the client countries. However, their commercial diversity (client businesses are from different branches) and the diversity of countries (80 countries) helps lower the risk to which the sector is exposed.

With the high specialization of the sector, many countries use the services of the PMI to obtain high quality products. Table 2 shows that of the total exports, 80% were to the European economic area, which highlights the following countries: Germany (27,97% corresponding to 88,893 million euros), Spain (16,94% corresponding to 53,836 million euros), France (13,53% corresponding to 42,985 million euros) and the Czech Republic (3,99% corresponding to 12,667 million euros).

Table 2 – Main destinations of Portuguese moulds in 2010
(units in millions of euros and percentage)

Main Clients of the Sector	2010	
	Millions of Euros	%
Germany	88.893	27,97
Spain	53.836	16,94
France	42.985	13,53
The Czech Republic	12.667	3,99
Mexico	11.710	3,68
The United States of America	11.669	3,67
The United Kingdom	10.964	3,45
Argentina	9.681	3,05
Poland	8.741	2,75
Brazil	8.030	2,53
Switzerland	8.003	2,52
Belgium	5.673	1,79
Holland	5.381	1,69
Russia	5.380	1,69
Slovakia	4.004	1,26
Others	30.188	9,50

Source: AICEP (2012)

Despite the diversity of customer industries, in Figure 2 the importance of the automotive industry for the PMI, representing 72% of its total production (compared with 14% in 1991 (Cefamol, 1996)) is evident, clearly outperforming the of home appliances industries (6%) and packaging (5%), among others, which reveals some vulnerability in Portuguese moulds production (72% of exports in 2010 was assigned to the automobile industry) (Cefamol, 1996).

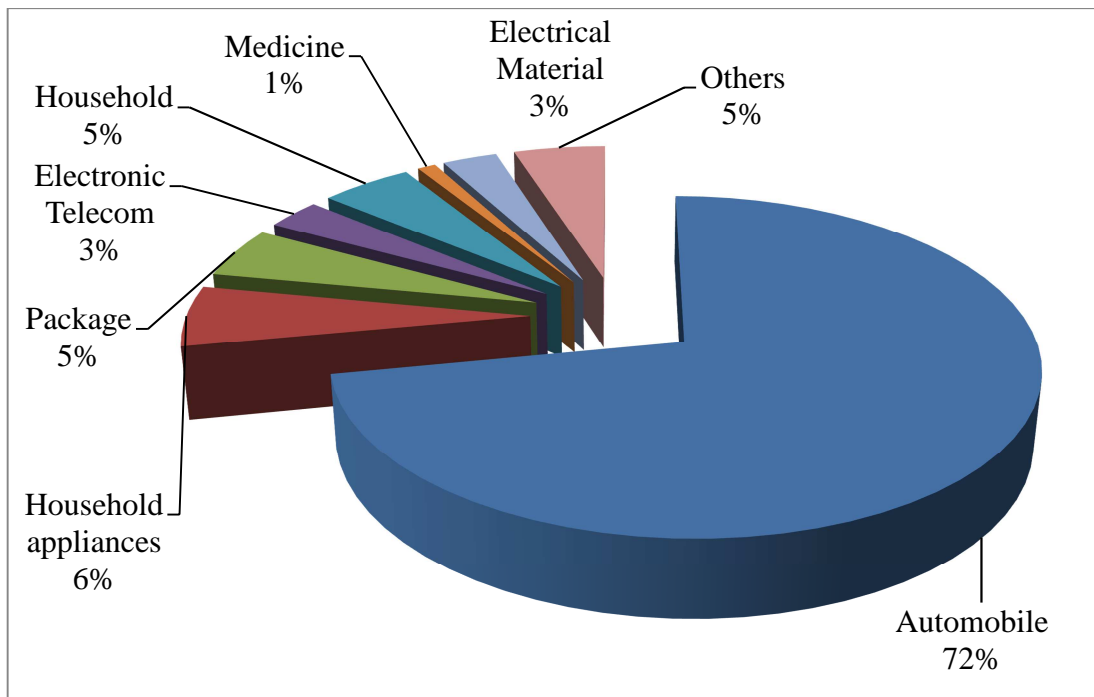


Figure 2 – Main client industries in 2010

Source: Cefamol (2011)

Joaquim Menezes (president of the Iberomoldes group) said in an interview to Invest Magazine (2011), that from April/May 2011 (which intensified in the summer months), Portuguese companies of moulds for plastic injection verified an increase in orders from customers in Europe, including the automotive industry, despite being the *”sector where there has been a retraction in the previous three years”* (Invest, 2011:10), a fact corroborated by businessman Leonel Costa in that magazine. The acquisition of new customers and the return of others, leads the entrepreneur Joaquim Menezes (Invest, 2011:10) to state that *”installed capacity to meet deadlines”* is complicated because the industry reveals some difficulty in satisfying demand. In addition to the automotive sector, also the electronics, electric, medical and pharmaceutical industries are also ordering moulds for new products (Joaquim Menezes, 2011; Leonel Costa, 2011 in Invest, 2011:10).

Moreover, along with the changes and transformations in the markets, companies are now in a transition phase (the transition management for the next-generation family, except for rare exceptions) (Cefamol, 2011), which allows the industry to rely on a new generation of better prepared managers, with increased and better knowledge, critical to

the fierce competitiveness of the current markets, as illustrated by the results presented for exports by China and Japan in 2009 (see Table 1): 13,99% and 11,47%, respectively (AICEP, 2012).

5 LITERATURE REVIEW

This section of the dissertation will focus on the milling process of the PMI and its optimization from a sustainable perspective, which implies the clarification of the concepts of optimization, sustainable development and sustainable companies.

5.1 Sustainable Development

The concept of sustainable development first appeared in the Brundtland Report of the UN in 1987 (UN, 1991):

“The development involves a progressive transformation of economy and society”, by which “Sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland Report, 1991:46).

However, what is sustainable development, that is to say, that which can actively contribute to social transformation that does not compromise future generations and meets the needs of the current, is envisaged in different ways by different authors, in spite of the fact that they all consider the economic, environmental and social axes. Thus, Hoffman and Bazerman (2008) focused on the eco-efficiency, corporate social responsibility, transparency and inclusion. Pereira (2009) argues that sustainable development depends on the dynamic balance between the three pillars of wealth generation, environmental protection and social inclusion. Loures (2009)⁸ emphasizes the previous idea by stating that the defence of sustainable development is the defence of human societies and, in particular, of the organizations that depend on the processing mode, for example, how to organize production processes.

⁸ *in* Vasconcelos e Filho (2009)

Ferreira (2010) used an inquiry based on another existing one elaborated by “Boston Consulting Group” and the “MIT Sloan” in order to better understand the connection of sustainability to the formulation of business strategies. This survey was conducted using 350 individuals working in different sectors such as education, industry, services, among others. For this, Ferreira (2010) considered it important to know what people linked to a particular occupational field mean by sustainability. Their study supports its conclusion that sustainability is a concept that generates some disagreement over its definition, because the concept chosen by the most respondents (48%) was presented in the Brundtland Report (1991:46), probably because it is a broader and more popular perspective. The other responses associated the concept only with its environmental aspect, others with the maintenance and financial viability of a business, excluding the environmental and social aspects, which shows a partial view of the concept.

Ferreira (2010) argues that sustainable development involves the creation of new solutions for problems and the implications of this form of development (long-term perspective, savings, optimization and efficiency, cooperation and interdependence) are transversal to any area. However, he warns that the resistance to change and the dependence on the leadership can hamper the implementation of sustainable measures (reducing waste, improving energy efficiency solutions, "clean" energy, reduction or elimination of emissions of greenhouse gases, among others).

In this framework, the author considers sustainable development to mean the implications in costs reduction and the environmental impact of companies that derive from new solutions adopted in the production process and, ultimately, aim not to compromise the present and future generations regarding the availability of natural resources, since the United Nations (2011a) indicated resource scarcity as the challenge of the century.

5.1.1 The sustainability of the company

Ferreira (2010) states that the adoption of solutions that contribute to the sustainability implies a long-term perspective, optimization and efficiency, cooperation and interdependence which enables savings to be made. From this perspective, optimizing the production process at the stage of milling implies the adoption of new solutions that

contribute to business efficiency and saving resources, making sustainability an ally of competitiveness.

Effectively, sustainability will prove to be crucial in the medium and long term for the competitiveness (Young, 2007; Ferreira, 2010) and companies that can develop strategies to address the shortage of resources (energy, manpower, consumables, etc.) will gain in competitiveness (Epstein, 2008; ONU, 2011b).

Sustainability improves the company's image and costs reduction, giving a competitive advantage, because sustainable organizations are those that adopt strategies that make them economically viable and competitive caring for the environment and contributing to the development of the region/country in which they operate (Almeida, 2002; Leal, 2009)⁹. Thus, sustainability is a business opportunity and not an obstacle to development (Ferreira, 2010), because it actively contributes to the transformation of business and its competitive advantage.

Gomes (2009), in a case study in Corticeira Amorim, interviewed five managers of the organization¹⁰ and concludes that because of the uniqueness of the company's managers, they understand sustainability as an intrinsic characteristic of the development of the company. According to the general director of Amorim&Irmãos, sustainability has brought the company gains in the "*market share, innovation, differentiation, operational efficiency with energy savings that already exceed half a million Euros*" (Gomes, 2009:71), a fact that, in 2009, allowed the company to be "*distinguished by the Program Motor Challenge (from the European Commission) for improving energy efficiency*" (Gomes, 2009:72).

From interviews conducted with managers, it also underscores the relationship of sustainability with the globalization of business since these issues "*already had relevance in markets such as Australia, USA and others before being debated in Portugal*" (Gomes, 2009:70), and in terms of the market, having customers looking for your products because they are sustainable, which they consider "a factor to differentiate the company from their competitors" (Gomes, 2009:71), that

⁹ in Menezes *et al*, 2010

¹⁰ "Jorge Peixoto, general manager of Amorim Florestal; Vítor Ribeiro, general manager of Amorim & Irmãos; Jorge Santos, general manager of Amorim Revestimentos; Paulo Oliveira, general manager of Amorim Cork Composites and Paulo Bessa, manager for Corporate Sustainable Development of Corticeira Amorim, S.G.P.S., S.A." Gomes (2009:44)

“happens mainly by improving the image in terms of products and the level of credibility and professionalism of the company that 'help sustain the business' and reinforce the 'institutional and international recognition' of Corticeira Amorim ” (Gomes, 2009:71).

In this sense, Ferreira (2010) also concludes that there is an urgent need to develop and implement sustainable practices, whose benefits have repercussions *“primarily in terms of improving the corporate image, but also in costs reduction, in the competitive advantage acquired or in the innovation of the business model”* (Ferreira, 2010:99).

In the specific case of the PMI, it is important to note that the industry has to be mobilized in order to help the customers, with the *“introduction of new ecological models in the market”* (O Molde n.º 89, 2011) and, as El-Hagggar (2007) adds, these *“new ecological models”* may go through new technologies (equipment), new forms of machining (such as sustainable milling), or even new more environmentally friendly injection materials. The fact that the sustainability contributes to improving the company's image among customers, which, besides being a competitive advantage, can contribute to the internationalization of companies (Gomes, 2009), is particularly important in an industry with such a high emphasis on exports as moulds.

5.2 A sustainable company

According to the above, the development of sustainable practices, such as the optimization of milling process, are fundamental to the company's competitiveness. A sustainable company (see Figure 3) is an eco-efficient company, which reaches higher production levels with less use of resources and fewer negative impacts on the environment (Melo, 2006; Oliveira, 2008).

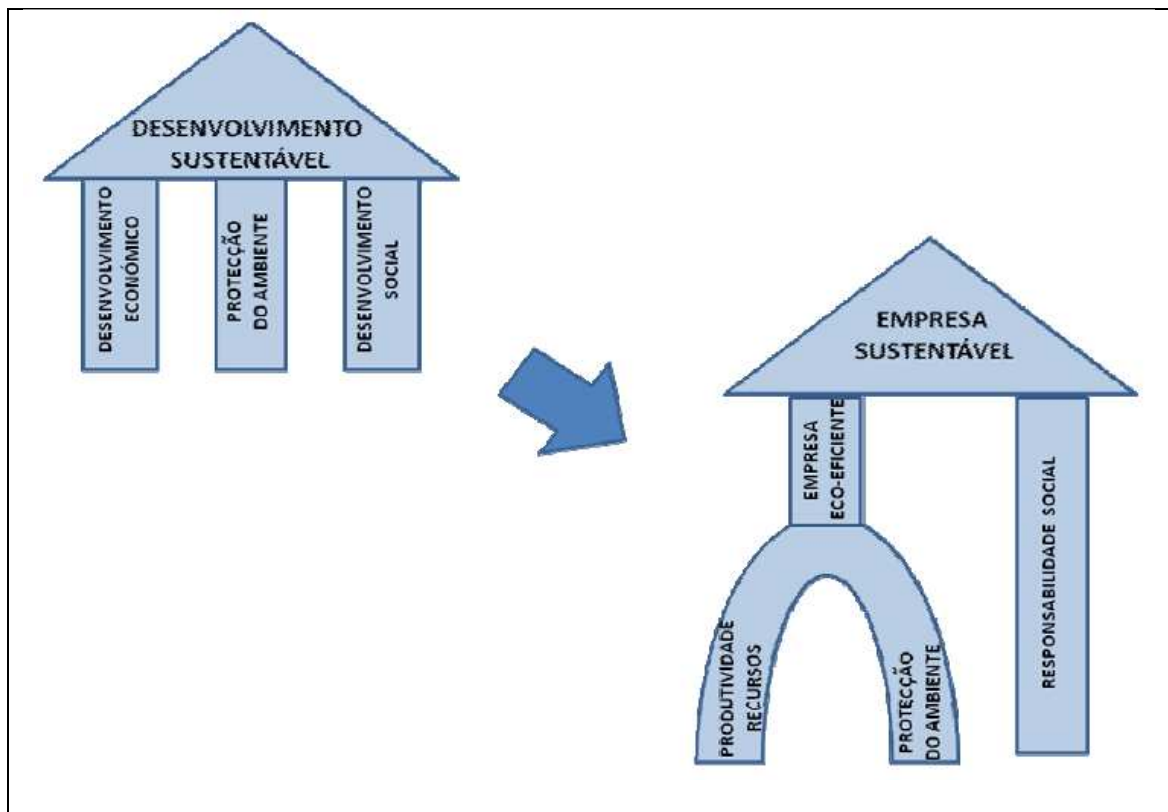


Figure 3 – Concept of sustainable company

Source: Oliveira, 2008:18

Ecoefficiency promotes the production of wealth through the use of fewer resources, making it an indispensable tool for sustainable development. The concept was originated in 1992 by Stephan Schmidheiny, and, in general terms, argues that economic growth and environmental protection are not conflicting goals and that the industry does not have to be necessarily part of the problem (Oliveira, 2008), as eco-efficiency permits reconciliation of production efficiency, cost reduction and the sustainable use of resources (Lins and Wajenberg, 2007¹¹).

Jorge (2011) conducted a case study on the company Esporão S.A. about water consumption in the production process of wine, important to the company, since water is a “*structural and strategic natural resource, being an essential factor for the company’s economic development*” (Jorge, 2011:1). As water is a strategic resource and structural for the wine production process, so is electricity to the PMI. Therefore the

¹¹ in Menezes et al, 2010

study was considered important due to the fact that it was implemented in the productive context in Esporão S.A..

Jorge (2011) found that in the period 2003-2009, the ratios of water consumption in the production process and the amount of litres of wine produced in the firm had a mean value of 3 points per litre of water consumed vs. litres of wine produced, a long way from the 0.75 produced in France and Italy.

Thus, the study aims to identify at which time of the production process it is possible to reduce water consumption, so as to be able to adopt ecoefficient solutions to improve the company's competitiveness and the development of processes that have mitigated environmental impacts. After identifying the activities (20% of the total) in which 80% of the water consumed was used some changes in the process of sterilizing bottles were suggested, in terms of the times of activities and equipment used, for example, and the results were measures after this.

The analysis of the ratios of water consumption per litre of wine produced reveals that there was a decrease in consumption for the period 2006-2009, despite not reaching the values presented by other countries, as has already been mentioned.

According to Jorge (2011:8) it can be concluded that not only is it critical to acknowledge water consumption as an important factor for the sustainability of the company, as well as reducing these consumptions, because *“operations and processes efficiency are important for the economic and environmental sustainability of business”*, whereby Esporão S.A. will adopt the same methodology for energy consumption during the production process, in order to make it more efficient.

It is important to note that the study by Jorge (2011) on the Esporão S.A. involved the detection of gaps in the production process and the developing of strategies to minimize labour costs by reducing the water consumption, which contributed to the economic and environmental sustainability of the company. In this sequence, the study of this dissertation intends to examine how far the optimization of the production process, by the use of a sustainable milling process, allows the workforce available to be restabilised and the energy consumption to be reduced, contributing to the economic and environmental sustainability of the company.

5.3 The concept of optimization

Mathematically, the concept of optimization refers to the study of problems in which one seeks the extreme (minimum or maximum) of a function, by systematic choice of the values of real or integer variables, (Ravindran, Ragsdell e Reklaitis, 2006).

Thus, the mathematically-minded consider that in any optimization problem, there are two general questions (static and dynamic) that have to be asked and consequently answered, namely:

- How can it be stated that the point X is the optimal solution? (static question);
- If X is not the optimal solution, then what is? (dynamic question). (Ravindran *et al*, 2006).

Sun e Yuan (2006) state that from the exploitation of theoretical possibilities, intended to restructure a certain "problem", the best possible decision under real conditions must be looked for in order to obtain the highest possible yield, by creating the most favourable conditions for the solution that, among all possible solutions, leads to the most satisfactory results.

In this study, a sustainable milling is proposed which happens by finding an alternative to the current "point X" (dynamic question), that is to say, reducing machining times without decreasing the quality of the final product (moulding zone).

5.4 The production process of the Portuguese Moulds Industry

The study of this dissertation will be in the section of the milling, during the execution of the core and the cavity of the mould. Milling is one of the mould machining operations, using tools with multiple cutting edges disposed regularly around a rotation axis (Sun e Yuan, 2006).

In the PMI, milling is considered the 'heart' of the production process of the mould industry, because most of the pieces pass through this section. As Weinert, Enselmann and Friedhoff (1997:325) stated "*the fastest and most economical way to produce moulds is the direct process of milling compared to the technology of erosion*". In this

follow-up, optimizing the production process at this stage, allows the company to increase competitiveness and profitability.

Figure 4 allows us to better understand the production process of the mould and the location of the stage of milling. It can be verified that the sections are closely linked, either in a sequential relationship, or in a parallel one. Only effective coordination from the specificity of the mould and the company structure, particularly in the production sector, allows positive results to be achieved.

For Sönmez *et al* (1999), production time consists of the preparation of the machine, its loading and unloading, the adjustment process and the rapid advances, machining and tool change.

This study focuses on the optimization phase of the milling by adjusting the cutting parameters (axial and radial increment of the tool) in the adjusting areas of the mould cavities and cores, to reduce the simulation time. Bieker (1991)¹² states that “*for a more economical machining, one of the most important prerequisites is to have optimal cutting conditions*”. The cutting parameters will be collected from various sources: the software used, programmers and developers who work with CNC technology. This factor is important because each piece has a different geometry, which implies that all these cutting parameters have to be adjusted to the geometry to be machined (Park e Kim, 1998; Hatna *et al*, 1998).

Efficient cutting parameters in milling have been a problem for almost a century and now, more than ever, the optimum parameters for milling remain a major concern for the production phase, having a great need to optimize them for their high importance in today's world of manufacturing (Tolouei-Rad e Bidhendi (1996), Cefamol (1996), directly influencing the production times (base of this investigation). The cutting parameters to specify this study will be:

- axial increment (tool's displacement in Z, by levels) (ap);
- radial increment (lateral displacement of the tool) (ae).

¹² in Weinert, Enselmann and Friedhoff (1997:325)

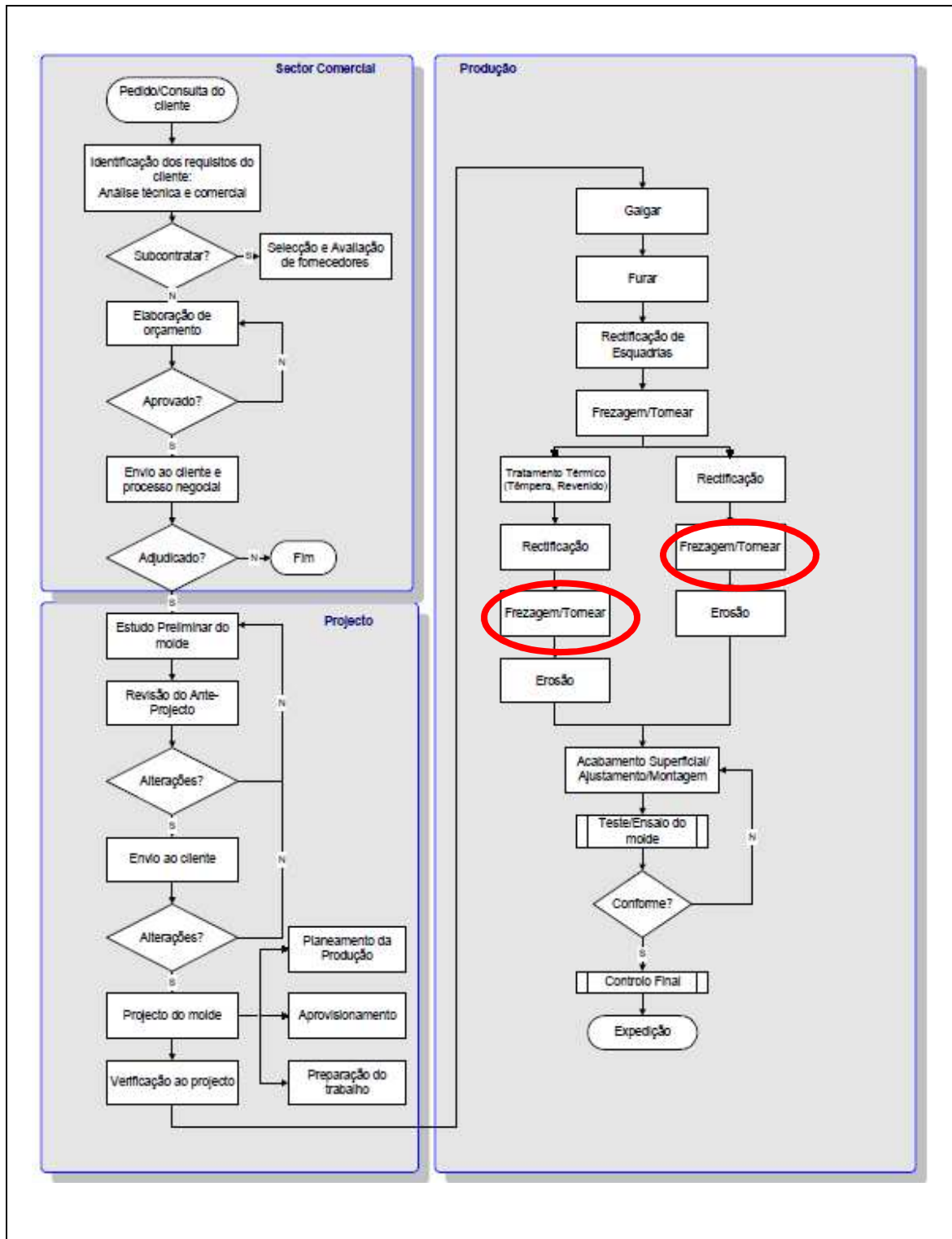


Figure 4 – Process of design and manufacture of moulds

Source: Ferreira, 2001:34

Using the two factors presented above, it is possible to get the parameters used in CNC and, as Agapiou (1992) defends, there are three fundamental parameters for the optimization of machining in CNC machine tools. These parameters are:

- maximum rotation (S) possible;
- minimal (in the tool to steel approximation) and maximum feed rate (F) (cut) possible;
- maximum (possible) axial (a_p)/radial (a_e) increment of the cutter at the moment of the cut.

A fundamental problem observed in the application of the cutting parameters recommended by the manufacturers is the difference between the conditions that result in laboratory and real working conditions. Tests conducted by the tool vendors are performed under optimal conditions and are inadequate in relation to the reality of manufacturing moulds, that is to say, the tests are carried out in a controlled environment (constant temperature), with adequate equipment for the tool, for example, while the temperature in firms is not constant and it is often necessary to adapt the tools available in the market to the machinery of the company. Consequently, CNC programmers and operators have to lower the recommended cutting parameters values, adapting them to the conditions of the equipment, tools and accessories, among others. According to Adamczyk (2004), the choice of the cutting parameters determines the test results of tools used in production, which can be very similar to the 'real' (machining conditions), and various criteria such as tool wear and specifications of the process of machining should be taken into account.

The *Tekniker IK4 Research Aliance* (2008) conducted a study in order to compare the conventional machining times, with the high speed and high performance machining, resorting to changing the cutting parameters used, as is shown in Figure 5. What distinguishes the three types of machining is the cutting speed which ultimately enables an improvement to be made in the final times. For example, the high speed milling has a shear rate of 5 to 10 times higher than the conventional milling for the same material.

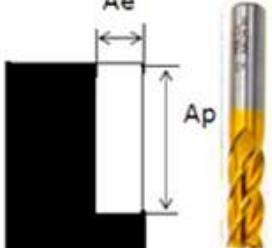
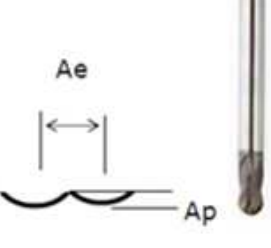
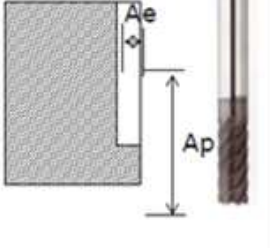
	Método convencional	Alta velocidade	Alto rendimento
R.P.M.	30-2.000	12.000-42.000	1.000-18.000
Avanço mm/min.	30-300	1.000-20.000	500-10.000
Prof. de corte (mm)	Ap: 10-15 Ae: 2-5 	Ap: 0.3-4 Ae: 0.3-1 	Ap: 10-15 Ae: 0.5-1 
Fresa Ø10mm			
Volume extraído	1-20 cm ³ /min.	1-60cm ³ /min.	1-150cm ³ /min.

Figure 5 – Cutting parameters of conventional machining, high-speed machining and high performance machining

Source: *Tekniker* (2008)

However, between the high-speed machining and the high performance machining other differences are listed besides the previously mentioned cutting parameters (see Table 3) that may influence machining times.

Table 3 – Differences between the high-speed machining and high performance machining

	High-speed machining	High performance machining
Magnitude range	Higher yield (cm ² /min.)	Chip volume per unit time (cm ³ /min.)
Programming	Milling volumetric 3D Complex surfaces	Milling volumetric 2D Determining factors ap, ae, fz
Machine capacity	3D milling capability High forward speed, dynamic, damping "lightweight construction"	2D milling capability High shear, high couple, rigidity and ruggedness
Filings/chips	Reduced volume of chips Thin floating and needle- shaped chips	High volume of chips
Areas of application	Printing and finishing Mould construction and finishing tools Milling roughing Thin-walled structures	Aerospace sector Construction of moulds and roughing tools Flat pieces and boards Boxes and cubic pieces Aluminium parts in serie

Source: *Tekniker* (2008)

In the high performance machining significant improvements are achieved, because the volume of material removed increases dramatically with the increase of cutting speed, which is translated in the tool advance (mm/min)¹³. Despite the high rate of material removal, the cutting forces applied on steel, through the tool, decrease dramatically, as the increment (axial and radial) is also less. Simultaneously, the machined surface quality is improved. As with any technique there are also less favourable aspects, as is the case of the tool life cycle, which decreases with the increase of cutting speed, therefore being subjected to greater wear (see Figure 6).

¹³ mm/min (mm per minute) is the unit of measurement of tool advance

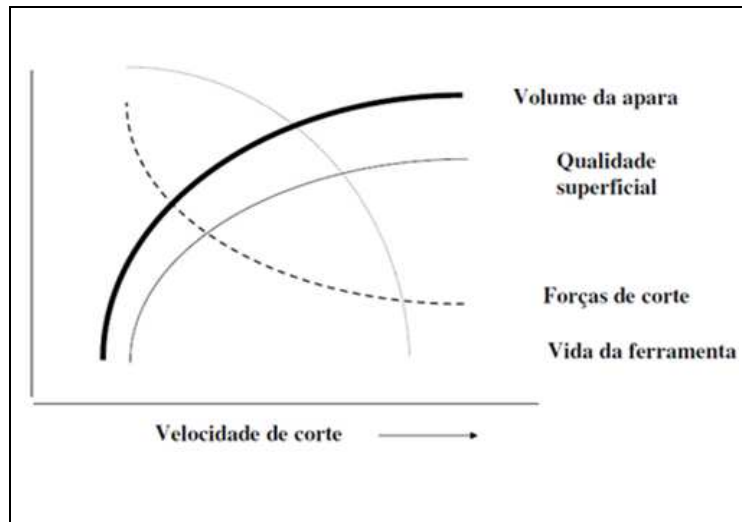


Figure 6 – Effects of increasing cutting speed of the tool

Source: *Tekniker* (2008)

Thus, *Tekniker* measured the times of attainment of different operations, using the three forms of machining presented above (Table 4) and concluded that the machining of high performance allows for a reduction of time in the order of 80% when compared to the conventional one.

Table 4 – Measurement of machining times – *Tekniker* study (2008)

	Conventional machining	High-speed machining	High performance machining
Machine roughing	58 min	20 min	11 min
Machining reroughing	28 min	26 min	26 min
Machining of prefinished	5 H 30 min	5 H 30 min	13 min
Termination of rays	11 min	11 min	3 min
Finishing plans	1 H 20 min	1 H 20 min	47 min
Finishing bi-tangency	24 min	24 min	10 min
TOTAL	8 H 46 min	8 H 11 min	1 H 50 min

Source: *Tekniker* (2008)

5.5 The optimization of the production process in the Portuguese Moulds Industry

The organization of the production process is increasingly important because, currently, customers require increasingly shorter delivery deadlines. Thus, it is necessary to reduce the production time, since this can influence the compliance with deadlines for moulds delivery.

To achieve this goal, the company can adopt two strategies: investing in more equipment or, on the other hand, making better use of the resources available in the company. Mukherje e Ray (2005:18) said in one of his articles that “*there is not only a single method for optimizing the process of metal cutting*”, therefore, in this study, the option was a sustainable strategy milling which implies changing the cutting parameters.

The objective is to observe, modify and measure times in one phase of the production process of the mould in order to make it more profitable, not for investment, but by adopting new ways of execution: changing the machining process, without altering the final finishing state of the molding zone piece, will allow the asset of the finishing quality, the feature of the PMI, to be maintained while reducing resource consumption, namely energy. Thus, it is important to identify the major problems in the accuracy of machining which, according to Weinert, Enselmann and Friedhoff (1997:325) have “*poor reliability in the process due to the variability between the cutting conditions especially in the prefinished stage; the cutting forces cause bending of the tool which in turn give rise to slight deviations causing imperfections in the milled surface*”.

To solve the problems identified, Weinert, Enselmann and Friedhoff (1997:325) presented as solutions “*adjustment of the cutting speed with the rotation using appropriate software*” and the possibility of “*compensating for deviation/flexion of the tool and tool compensation*”. Thus, the part used in the simulation (see Figure 7) conducted by Weinert, Enselmann and Friedhoff (1997:326) “*consists of surfaces with high degrees of tilt, and flat areas. The tools used were spherical and flat cutters. The machining was performed using software (not specified) that creates optimized toolpaths*”.

In the analysis of Figure 7, it can be observed, in the description, that differences between the 3D drawing (image B) and the machined part (image A) were obtained. These disparities are due to the fact that tool flexes in contact with the steel (while milling) causing wear, which causes small, but real, geometrical changes (which do not exist in the 3D drawing), either by excess or by defect relative to the nominal value of the three-dimensional model.

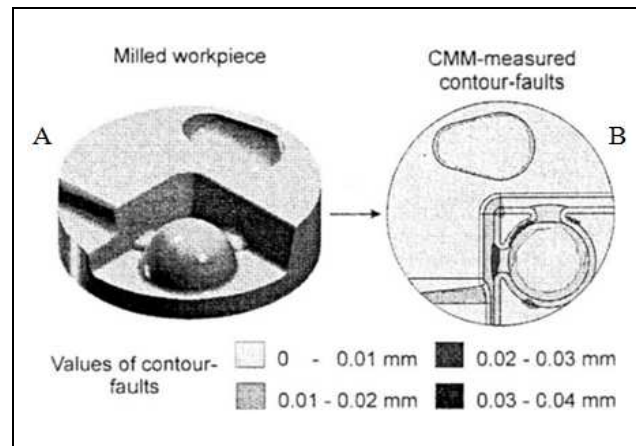


Figure 7 – Piece used by Weinert, Enselmann e Friedhoff (1997) for simulations containing the deviations caused by the tool after the experiment

Source: Weinert, Enselmann e Friedhoff (1997:326)

Machining conditions used by Weinert, Enselmann and Friedhoff (1997:326) were “performed at ambient temperature, steel with hardness used in moulds (1600 N/mm^2) and machined directly on the steel with technology for high-speed machining (HSC – High Speed Cutting)”. The results obtained by Weinert, Enselmann and Friedhoff (1997) in machining regarding the 3D geometry indicate that the optimum result is between 0,02 and 0,04 mm deviation, this indicates that the tool is subject to cutting forces which cause its bending, resulting in a cut sometimes by excess, sometimes by default. The authors further argue that to achieve satisfactory results in terms of surface finishing machined (values comprised between 0,02 and 0,04 mm), the ratio height/diameter of the tool can not exceed the value 5, as by using high tools (for profound machinations) the results of the surface finishing are less satisfactory. In this sense it appears that a height/diameter tool ratio different from 5 has to be used.

The ability to optimize the human resources allows the company to benefit, as well as its client, which will be satisfied with meeting deadlines (increased competitiveness) and the producer makes the most of the resources of the company. Improved management of some resources, particularly manual work and energy, will allow the mould that the customer wants to be delivered, with a lower production cost due to the efficient organization of the production process, a decrease in execution time of the work and improved efficiency of energy consumption, among other factors. According to El-Haggar (2007), by reducing the production costs, the company can keep the selling price of the mould, manage to increase the advantage generated by this and simultaneously reduce the environmental impact of the organization by minimizing various consumptions (such as energy and consumables). On the other hand, a service which until now could not be offered may be included in the mould, i.e., a greater reduction in delivery time maintaining the quality and increasing economic and environmental sustainability. These transformations affect the increase in suppliers, employees and customers' satisfaction, a better environmental and social performance and increasing income (Epstein, 2008).

The energy consumption and its impact on production costs are a challenge for companies and, in the following context, to reduce production times, it is particularly relevant since it directly influences the cost of the product and energy consumption by the company. It is also important to note that the reduction in energy consumption allows for a direct reduction in the emission of carbon dioxide (CO₂).

On January 26, 2012, NIE showed the industrial results for 2010 concerning the level of energy consumed in manufacturing, which includes the PMI. As shown in Figure 8, there was a general decrease in the production of carbon dioxide (CO₂) in the period 2006-2009.

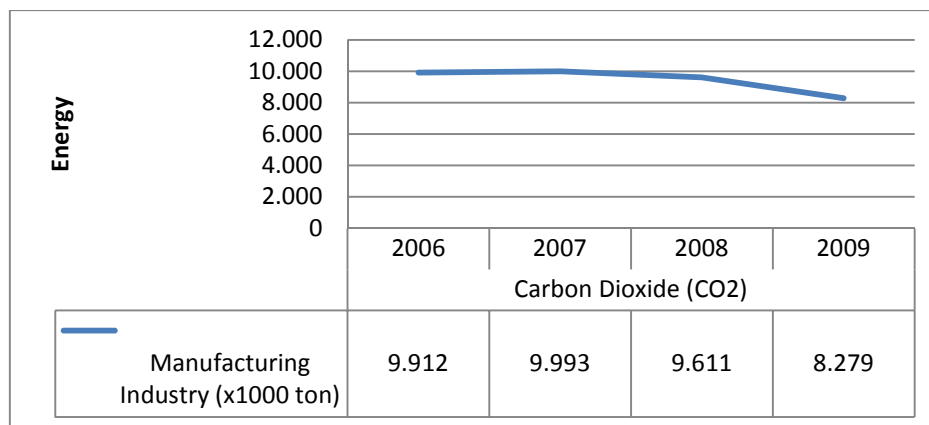


Figure 8 – Emission of carbon dioxide (CO₂) in manufacturing

Source: NIS, report Environment Statistics 2010, published in 2012 (NIS, 2012)

In line with the request made internationally by the UN (2011a) relating to scarcity of natural resources, the National Strategy for Energy (NEE 2020) aims to “*promote energy efficiency, consolidating the objective of saving 20% of the final energy consumption in 2020*” (NIS, 2012:25). The optimization of the production process in the moulds industry allows companies to contribute to energy efficiency, allowing not only “*the reduction of emissions by the energy sector*” (NIS, 2012:25), but also “*environmental sustainability of the energy sector*” (NIS, 2012:25) and increasing environmental and financial sustainability of PMI.

It is pertinent to note that, according to the NIS (2012), during the period 2006-2009, industry (in general) consumed 27% of electricity production, reflecting a decrease of 15% due to a decrease in industrial activity resulting from the global economic crisis which began in late 2008 (see Figure 9).

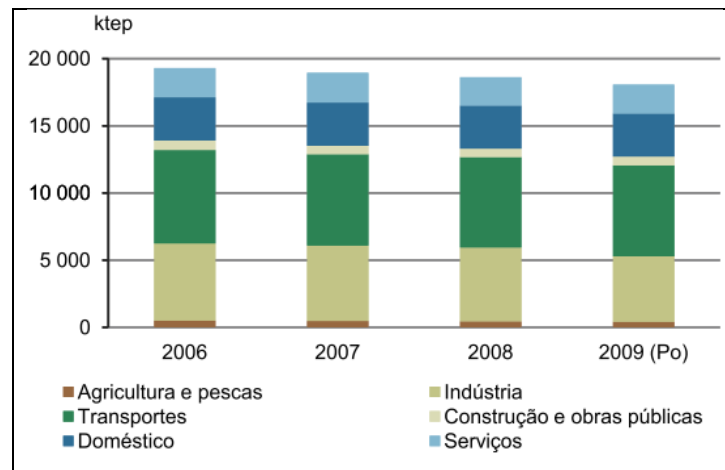


Figure 9 – Final energy consumption by sector

Source: NIS, report Environment Statistics 2010, published in 2012 (NIS, 2012)

6 Hypotheses

Based on the literature review, in the initial questions and the proposed objectives, it is intended to test the following hypotheses, namely:

H1 – The sustainable milling has a direct influence on the times of the production process.

H2 – The sustainable milling allows to reduce the time of man/machine to be reduced.

H3 – The sustainable milling allows to reduce the consumption of electricity to be reduced.

H4 – The sustainable milling allows to reduce the emissions of carbon dioxide (CO₂) to be reduced.

H5 – The sustainable milling applies to moulds of different tonnages.

H6 – The unprojected area of the adjustment zone influences the time of the production process.

7 Research Model

This research was conducted in terms of several interrelated concepts. So a research model was constructed:

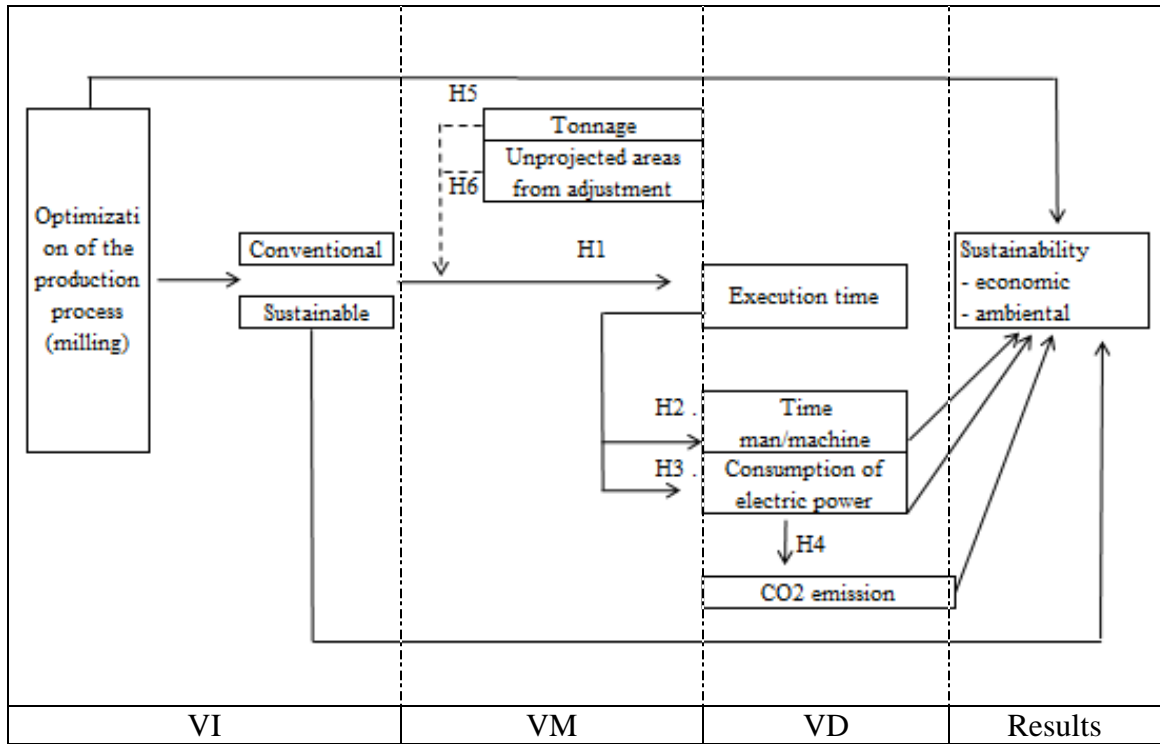


Figure 10 – Research Model

Own source

PART II

In the second part the process of devising research in all its stages is explained: collection of information, type of research chosen, the intended population, sample construction, characterization of the company where the study was conducted, the variables and the control and experimental groups, the collection and the definition of cutting parameters, the model of computer simulation, the software used and finally the internal and external validity of the study.

8 RESEARCH METHODOLOGY

Each research work requires a specific methodology with the objective of providing the researcher with a proper way to achieve the proposed goals, improving the understanding of them. So the context in which the study was carried out is characterized and the methodology that will allow the results to be presented will be explained.

8.1 Collection of information: primary and secondary data

According to Silva (1981), the use of computers achieves greater accuracy, thereby achieving better storage of simulation models, as well as greater flexibility in the construction of these models and programming done in software. Therefore, it was the defined medium to obtain primary data.

Primary information is characterized by the fact that it does not exist before developing a research project, since it is designed specifically for it. In this case, the primary data will be obtained by simulation, with the objective of validating, or not, the hypotheses to be tested at the end of the study. For this reason, these simulations will be carried out in a mould company in Marinha Grande, in the district of Leiria, Portugal.

In this investigation, it has been important not only to show how the information was obtained, but also its quality. Thus, the selection of information was made taking into account its relevance, accuracy and relevance, since all the data that exist and are available to be used are meant for secondary information. In this context, other investigations, scientific articles, scientific works, speciality magazines such as “O

Molde” and others with information relevant to this investigation were consulted. Importantly, during the process of gathering information, empirical studies similar to this in the sector of moulds were not found.

8.2 Type of research

In this thesis is intended to compare the times of conventional milling simulation with the times of sustainable milling (to be developed in this study). To achieve this purpose, the investigator chose an experimental investigation of causal predictive type (Fortin e Fillion, 2006; Sampieri, Collado e Lucio, 2006), since it is intended that a variable would have an effect on the other (Fortin e Fillion, 2006; Sampieri *et al*, 2006).

Thus, a population group of elements on which the study focuses will be used and will measure the effects of the variables defined.

8.3 Population

The population group studied in this dissertation consists of moulds for plastic injection produced at the company where the research took place, over a certain spatial and temporal range, during the year 2010. This group of moulds was chosen for two reasons:

- according to the management, it was a representative year of business activity;
- the company produces moulds for different sectors, which refers to an extensive market for the type of mould and tonnage.

Thus, the target population (56 moulds) used in the investigation was the whole production of moulds for plastic injection in 2010, in a company situated in Marinha Grande. However, the study focuses on a total of 112 pieces, because each mould has a cavity and the respective core, thus the machining simulation focuses on 56 cavities and 56 cores.

In this regard, each of the moulds will be assigned a sequence number for better identification in the results phase, thus the first mould cavity will be assigned 1C and the respective core (called Bucha in Portuguese) will be assigned 1B. Therefore it will be straightforward to identify that it is part of a particular cavity or core and of which

mould. Then an explanation of how the sample was constructed for this investigation will be provided.

8.4 Sample

To homogenise the target population by size of moulds (tonnage), before the study itself, the matching block was made by dimensions (tonnage) (Fortin e Filion, 2006), since these authors leave the option of being able to make it until before or after the study. As the pairing of blocks have different sizes a random sampling was made up with each stratum proportional to the population size, allowing “*the researcher to use a smaller sample and get the same degree of representativeness as with a larger sample*” (Fortin e Filion, 2006:317; Sampieri *et al*, 2006). The test sample consists of 36 moulds (maximum number of moulds that was established was analyzed through simulation, taking into account the time available for the realization of the dissertation), organized into strata (or classes) by tonnage, of which for each stratum, the quantity of moulds calculated based on the proportion of the sample relative to the population, in order to control the effects of this moderating variable.

As the National Association of Mould Industry (Cefamol) does not have a scale dimensioning of moulds, Rodrigues (2002:169) created one in his PhD Thesis, based on interviews conducted with 63 top managers of the PMI. The base unit for dimension of the moulds will be the ton. These classes are represented in Table 5.

Table 5 – Classes of dimensions of the moulds VS designation of the type of mould

(unit: tonne)

Dimension (Ton)	Designation of the type of mould
]0 ; 0,25]	very small
]0,25 ; 0,75]	small
]0,75 ; 2]	
]2 ; 5]	medium
]5 ; 10]	
]10 ; 20]	large
]20 ; ∞[	extra large

Source: Rodrigues (2002:169)

The moulds of the study population were classified according to the data listed in Table 5, which allowed all the moulds included in the study to be stratified (see Table 6).

Table 6 – Distribution of elements to consider in each stratum

Dimension (Ton)	Elements (Nh) ¹⁴
]0 ; 0,25]	3
]0,25 ; 0,75]	7
]0,75 ; 2]	23
]2 ; 5]	9
]5 ; 10]	8
]10 ; 20]	3
]20 ; ∞[	3
Total (N)	56

Resulting from the study (own source)

¹⁴ Nh is the value stratified, in other words, it is the number of effective elements to be analyzed in each stratum

From the sample size, it became necessary to find a factor (sh) that could homogenize the number of pieces to be drawn from each stratum, so there is equal representation of all strata (Fortin e Filion, 2006), once “*The stratification increases the accuracy of the sample and involves the deliberate use of different sample sizes for each stratum*” (Sampieri *et al*, 2006:259).

With this weighting (proportion to use in each stratum – sh), the probability of obtaining a representative sample (of moulds) increases, (Amyotte, 1996). Thus, Equation 1 presents the calculation method to find the factor of proportionality, in which N is the population size and n is the sample size.

Equation 1 – Proportion to use in each stratum (sh)

$$sh = \frac{n}{N} = \frac{36}{56} \cong 0,64$$

After calculating the proportion to use in each stratum ($sh = 0,64$), the sample for each stratum (nh_i) was calculated, using the multiplication between the proportion (sh) calculated in Equation 1 and the value initially stratified (Nh_i) presented in Table 6, which is the number of effective elements to be analyzed.

Equation 2 – Sample size for each stratum i (nh_i)

$$nh_i = sh * Nh_i \quad , i=1, 2, \dots, 7.$$

After finding the set number of moulds to simulate per stratum (nh_i), all the values resulting from Equation 2 were added up so as to form the sample investigated (n), i.e., size of the stratified sample.

Equation 3 – Size of the stratified sample (n)

$$n = \sum_i nh_i \quad , \text{ for each stratum } i (i=1, 2, \dots, 7).$$

Table 7, following Table 6, have the results from Equation 1, Equation 2 and Equation 3.

The stratified sample size used in this investigation is $n = 36$ moulds (36 cavities and 36 cores), making a total of 72 pieces.

Found after the sample size for each stratum i (nh_i), the researcher randomly chose what the representatives of each class would be to incorporate in the sample resulting from Equation 3 (probabilistic stratified sample n) and are shown in Table 7. This is known as probabilistic stratified sampling, because all elements of all classes have equal probability of being part of the sample, enhancing its representativeness (Fortin e Filion, 2006). The values obtained for each sample for each stratum (nh_i) are rounded off in the usual manner.

Table 7 – Classes of dimensions of the moulds (unit: tonne) with samples per stratum

Dimension (Ton)	Elements (Nh)	Percentage of sample elements given the size of the population (sh)	Sample by stratum (nh)
]0 ; 0,25]	3	0,64	2
]0,25 ; 0,75]	7		4
]0,75 ; 2]	23		15
]2 ; 5]	9		6
]5 ; 10]	8		5
]10 ; 20]	3		2
]20 ; ∞ [3		2
Total (N)	56			36

Resulting from the study (own source)

Based on the study results for the sample of 36 moulds (see Table 7) the value of the standard deviation of the population from the value of the sample standard deviation was estimated, in order to calculate an estimate for the level of accuracy of the results. In order for the confidence level to be high, the investigator worked with the degree of 95% and it was used the formula presented by Daniel and Terrell (1995), as expressed in Equation 4 (see below – Sample).

As the study done focusses on 36 moulds constituted by the respective cavities and cores (cavidades e buchas), an estimate for the execution times of both, from Equation 4 is presented in the chapter ANALYSIS AND DISCUSSION OF RESULTS (see Milling).

Equation 4 – Accuracy of the estimate relative to the differences of simulation times

$$d = Z \cdot \frac{\sigma}{\sqrt{n}} \cdot \sqrt{\frac{N-n}{N-1}} \quad ,$$

where in:

d – Level of accuracy of time estimation obtained from the sample. In other words, the maximum difference (or error) of the estimated time obtained with the sample against the time that would be obtained from the population.

Z – Value of the standardized normal distribution corresponding to the desired confidence level. In this study a degree of confidence of 95% was used, with the matching value for Z being 1,96.

σ – The population standard deviation (value for the estimate based on the results of the study for the sample of 36 moulds).

n – Sample size (36 moulds).

N – Population size (56 moulds).

8.5 Characterization of the company where the study was conducted

In 2010 (the period when this investigation began) the company where the study was conducted obtained the certification NP EN ISO 9001:2008 from TUV (Technischer Überwachungs-Verein – a German company of inspections and certifications) and earned 3,5 million euros from the manufacture of 56 moulds.

The machine park of the company in 2012 consisted of 9 CNC milling machines (the machining centers of 3 and 5 axes were included), 3 conventional milling machines, 3 turning machines, 6 rectifiers, 5 erosion by penetration, 1 wire erosion, 2 boring mills, 2 deep hole drilling CNC (one of 3+1 axes and another of 3+2 axes). It had 63 employees at that time.

8.6 Procedures for simulation

Using a software program for milling (creating the tool path for CNC machines), used on a daily basis in the company, it is intended to simulate two types of milling.

In the literature review conducted by the researcher, no study similar to what is intended to be done (chapter 5.5) was found, whereby two concepts were defined, in order to clarify the procedures used in the study, namely: simulation/sustainable milling and simulation/conventional milling.

Conventional simulation/milling is perceived as the one that actually takes place – is characterized by the same type of machining in the moulding zone and in the adjustment zone.

Sustainable simulation/milling is the alternative proposed in this study - implies the differentiation of finishes in the moulding zone and in the adjustment zone. In this type of milling the increment axial and/or radial one will be increased depending on the finishing operation.

These simulations will be performed on cavities and plugs of the sample selected from the 56 moulds (of different size/tonnage) produced in the company during the year 2010.

To achieve the proposed objectives (chapter 3.1) computer simulations will be made, in order to compare the times of conventional and sustainable simulations. To this end, machining software will be used (chapter 8.11), which is used daily in the PMI.

This method was chosen for data collection (simulation), since, according to Silva (1981), simulation used in the context of research seeks to establish the optimal values of the parameters that describe the process under study, allowing a more realistic and precise approach to the problem. Similarly to Weinert *et al* effected in 1997, the pieces simulated in this dissertation also contain surfaces “*with high degrees of tilt and flat areas*”, in which spherical and planar tools (see Table 8) will be used, using a software application “*that creates optimized toolpaths*” (WorkNc).

Figure 11 illustrates a cavity or a core with the demarcation of moulding areas (number 1) and adjustment zones (number 2). Some moulds may have one or more moulding cavities, whereby two zones are presented with number 1.

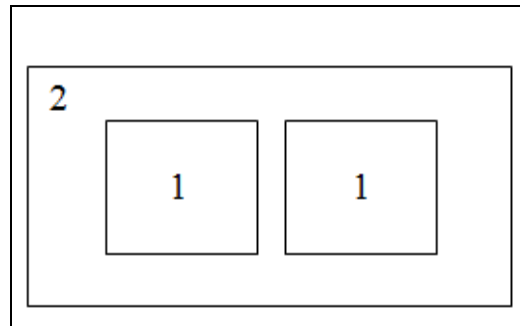


Figure 11 – Identification of moulding zone (1) and adjustment zone (2) in a mould

Own source

When machining, many programmers do not distinguish the moulding zone (number 1 in Figure 11) from the adjustment zone (number 2 in Figure 11), making only one machining window or a mixed machining (the same window contains part of the moulding zone and part of the adjustment zone), with results in a unique milling. Thus, the adjustment zone maintains the same level of quality of the moulding zone. This approach is referred to as simulation /conventional milling, as described above.

The milling (sustainable), proposed in this dissertation, consists of using two windows for machining, to maintain the traditional finishing level in the moulding zone (first machining window – number 1 of Figure 11), while in the second machining window (number 2 of Figure 11) a finishing of good level is intended, but with a different quality from that effected in the first window (increasing the lateral or axial passage, according to the operation). Thus, the "soul" of the mould is the moulding zone, while the adjustment zone has the functions of defining and supporting the mould closing force.

The so-called "joint line of the mould" (imaginary line where the mould is opened) allows the separation of the cavity and the core and the 'demolding' of the plastic piece. In the design phase, the joint line is set after the completion of the plastic piece and, therefore, it is the complexity of the demolding of the plastic piece which will define the complexity of the joint line, which is reflected in the adjustment line of the cavity and of the core.

At the time of mould assembly (section of the workbench), bench operators have to ensure that the adjustment zones of the core and the cavity rest against each other to maintain the same interval over the entire molding area. This way when injecting the heated plastic (liquid), it does not leave the molding area. When these technical aspects are not achieved, the raw material invades the adjustment zone, giving rise to the barb part.

Even if the finishing of the adjustment zone is perfect and the milling respects the 3D program, the collaborators of the workbench always need to adjust it, to ensure that the adjustment zones of the core and the cavity overlap, preventing infiltration.

In summary, programmers have to maintain the quality of the surface of the moulding area, as is currently done, and may sacrifice the surface quality of the adjustment area (compared to the molding zone), increasing the axial and radial increments (depending on the finishing operation), in order to reduce milling time.

Throughout the process, the programmer must take into account the quality of the surface finishing of the adjustment zone, so that during assembly (section of the workbench) the operators do not have further work, due to the excess of material or excessive roughness in the adjustment zones, for example.

Thus, simulation times (conventional and sustainable) are recorded by the researcher for the same kind of mould and subsequently compared, in order to determine possible time differences, in order to optimize the production process and allow savings in the use of resources.

After obtaining the times, it is intended to simulate what the influence they have on the average power consumption by the machining equipment will be, the amount of carbon dioxide (CO₂) emitted or not emitted by power consumption, as well as the hours of man-machine necessary for the realization of such simulations (conventional and sustainable).

The obtained results will allow conclusions to be drawn to then confront with the questions and hypotheses raised in this study.

8.7 Variables

As mentioned previously this is a predictive-causal research, more properly an experimental study, which involves presenting the definition and the operationalization of variables.

According to Tuckman (2000) and Fortin and Filion (2006), the independent variable (IV) is the element that is introduced, manipulated and selected by the researcher to determine their relationship to the observed phenomenon, that is, the dependent variable (DV). The IV is modified by the investigator in order to assess their influence on the DV, i.e., is a necessary cause of a particular result; is what causes an effect. So, what is studied is how this factor is reflected in another. Fortin e Filion (2006:171) also claim that *“the independent variable, also called experimental variable is regarded as the cause of the effect produced on the dependent variable”*.

Tuckman (2000) refers to the fact that DV is the factor observed and measured to determine the effect of IV, i.e., DV *“is suffering from the effects of the independent variable; is the result predicted by the investigator”* Fortin e Filion (2006:171). This DV is also called variable criterion or explained as variable by Fortin e Filion (2006).

In this study, besides IV and DV, moderating variables (MV) will also be defined, since it considers the possibility that these influence the relationship between DV and IV presented above. The MV is a secondary independent variable, selected to determine if it affects the relationship between the key independent variable and the dependent variable (Tuckman, 2000):

“If the researcher is interested in studying the effect of the independent variable X on the dependent variable Y, but suspects that the relationship between X and Y is modified by the level of a third factor Z, then Z may appear in this analysis as a moderating variable.” (Tuckman, 2000:126).

In this context, it is X (IV) the types of simulation (conventional and sustainable), Y (DV) the resulting time of the simulation performed, energy and human resources and Z (MV) the scale (tonnage) of the mould, the mould adjustment zone, the not projected area of the adjustment zone, the hardness of the steel in the milling process (2311, 2344, 2738, 2738HH, among other hardnesses), the machines of the company, the piece geometry, among other factors, as it 'is suspected' that these moderating variables

directly affect the relationship between the independent variable and the dependent variable.

The control variables (CV) are *“factors controlled by the experimenter, to cancel or neutralize any effect that it could otherwise have on the phenomenon observed.”* (Tuckman, 2000:129). This is the reason why, as mentioned above in procedures for the simulation chapter, only change between simulations the axial increment (operation in level Z) and radial (copy operation) depending on the type of operation to be performed, not changing any other technical parameter in the programming stage (feed, speed, among others), in order to neutralize any influence of these factors on the results of the study.

The extraneous variables (EV) or parasites *“are present in all studies and may have an effect on other variables and influence the results of an investigation”* (Fortin e Filion, 2006:172), whereby, according to Fortin and Filion (2006) the role of the investigator is to reduce the effects of these variables to a minimum. Thus, the researcher performed the simulations (conventional and sustainable), in order to reduce the effect of the EV in the study. However, there are several factors that influence the daily machining and actual running times, in other words, in the same way as the materialization of the simulated programs (conventional and sustainable) makes up the same conditions (the equipment, developer, type of tools, the period/season, among other things), there are always anomalies that are inherent in the process and which cannot be controlled (VE), such as tool breakage, tool wear and ambient temperature among others. However, despite what has been said, studies like this are more viable by simulation, because *“actual experiments are more expensive than the Simulation Models”* Figueiredo (2010:19).

8.8 Control group and experimental group

Tuckman (2000:171) designates the control group as *“a group of participants in a certain experiment, whose selection and experiment are as similar as possible to the experimental or treatment group, except that they are not subjected to this treatment”*.

In contrast it appears that the experimental group is the group which will be subjected to a manipulation of variables, which will mean that different results could be achieved.

Although the 36 randomly chosen moulds are submitted to the simulation phase, it was decided to designate the one in which the conventional simulation occurs as the control group, for two reasons that are interconnected:

- it is the simulation that is currently being use in the manufacture of the company where the study takes place;
- it is the conventional simulation that will be the starting point to draw conclusions about the study.

The experimental group will be the one in which the sustainable simulation will occur, in other words, that where the researcher will effect the manipulation of the IV (axial and radial increment), to be possible to achieve effects on DV (machining times).

8.9 Collection and definition of cutting parameters

In the construction of the finishing program (NC - Numerical Control), using the machining software WorkNC, the researcher only changed the radial increment (lateral displacement of the tool) using a finishing strategy per copy (an operation where the tool path follows the 3D contour) in which spherical endmills, and an axial increment (in Z) with the use of machining strategies by levels in which shallow (straight) endmills were used.

To obtain cutting parameters which were more optimized for finishing, the adjustment zones resorted to various sources, as stated earlier: software, programmers and CNC operators. Therefore, the following table (see Table 8) presents values that programmers and CNC operators usually use to create these NC programs. In that table, there are some spaces with "no value", which is justified by the specific nature of the operation to be used in machining these pieces, i.e., mostly spherical milling cutters are used in copy operations, only radial increment existing in this case, while the shallow endmills (straight) are used in programs with increments in Z, with an increment axial existing in this case. The values suggested by the software will also be presented. However, the values for the axial increment (Z) must be set according to the tool to be used, as the software makes no suggestion.

From the minimum values (data provided by the CNC programmers and developers) and the maximum values (data from the software) values for the construction of sustainable simulation programs (see Table 8) are suggested.

Table 8 – Synthesis of cutting parameters

Type of milling cutter	Diameter of the cutter (mm)	Conventional		software	Sustainable	
		Radial (mm)	Axial (mm)	Radial (mm)	Radial (mm)	Axial (mm)
Spherical top	6	0,2	No Value	0,288	0,25	No Value
	8	0,25		0,332	0,3	
	10	0,25		0,372	0,3	
	12	0,25		0,4	0,4	
	16	0,35		0,47	0,5	
Top shallow (straight)	6	No Value	0,1	No Value	No Value	0,15
	8		0,1			0,15
	10		0,15			0,2
	12		0,15			0,225
	16		0,15			0,25
	20		0,175			0,3
	25		0,175			0,3
	32		0,2			0,35
	35		0,2			0,35

Resulting from the study (own source)

8.10 Model of Computer Simulation

Silva (1981:322) believes that “simulation can be defined as any attempt to obtain information about a process by performing calculations based on a mathematical model that describes this process” and Robinson (2004) understands the simulation as an imitation (computer) of a resource configuration combined to provide goods or services. From this perspective it is Silva (1981:322), who states that “*obtaining information on*

the process or system under study is performed by a computer and is translated into the identification, adjustment of the study, of their characteristics, parameters and behaviours”.

Going further, Silva (1981) adds that the importance of conceptual models described and analyzed in terms of classical mathematics was influenced by the resolutions obtained by using the computer, since they have more realism, which leads to more accurate solutions.

The simulation method has the very important advantage of allowing “*empirical approaches based on trial and error*” (Carvalho, 2007:7), that is to say that, “*even when using simulation software, recourse to this methodology by performing successive simulations with different values for the process parameters is frequent*” (Carvalho, 2007:7). Thus, it is possible to apply different values for the same three-dimensional model (3D file), in order to find the optimal value for the piece in question.

Figueiredo (2010) states that the simulation models can deal with much more complex problems compared to mathematical models. Thus, simulation can be applied to hypothetical situations and real situations (as is the case in this study), with the advantage of it being a reliable and more economical alternative than the experimental method:

“actual experiences are more expensive than the Simulation Models, especially if something goes wrong. Although it may take a considerable amount of time to develop a simulation model, once completed, which allows the modeler to simulate months or years of the system behaviour in seconds, something that is not achievable with experiments” Figueiredo (2010:19).

The economic factor is extremely important, as the sector of moulds produces an extremely costly product, which makes it impossible to duplicate the machining of the moulding areas (cavities and cores), under the same conditions (machine-tool, tools, operators, environmental conditions - thermal - among others). On the other hand, a mould is a tool-prototype whereby replication would entail waste, since this second mould would not be used.

For the above reasons, the simulation process was chosen to conduct this research as it is the most appropriate way, from the perspective of the researcher, to collect the times

of the different machining processes. What also contributed to the decision was the fact that, with the simulation, it is possible to adjust the features, parameters (axial increment or radial increment) and behaviours (Silva, 1981) from the tools to the strategies used (conventional and sustainable), in a faster Figueiredo (2010) and economic way compared to the materialization of the simulations.

8.11 *Software used*

The software chosen for data collection (WorkNc) is a program used on a daily basis in the companies specialising in the production of moulds, which proves the reliability of the results of this study.

8.11.1 Methodology for development of the simulation model

To work with the WorkNC software, a 3D file in IGES format (most common) or other compatible format is mandatory, because otherwise it will not be able to import the file to the work area of the software. The second step is to define the windows for programming, outlining the areas to be machined (moulding zone and adjustment zone).

Then the data must be introduced so that the software can generate the toolpath. For this, it is necessary to open a window for compiling programs (see Figure 12), which corresponds to a machining operation in a given location of the workpiece, with a particular tool and respective cutting parameters (axial increment or radial increment according to the operations), as well as other details intrinsic to the process/program NC.

Through the strategy (roughing, pre-finishing, finishing or another) to use in the piece, in 1 the operation or the type of route intended (copy, level Z, contour, tangent, etc.) is defined, that is to say, what the tool is intended to perform in CNC.

In 2 the area of machining is defined: as it may be chosen to machine in the Z axis or in another direction, as is the case of equipment working in 3+1, 5 or more axes. Despite, at this moment, being able to indicate all the surface of the piece, the programmer has the possibility to choose in which 3 specific areas he wants to run, that is to say, can opt

for machining the whole surface of the piece or select an area/window to machine, which corresponds to the initially created machining window.

In 4 the tool to be used in the selected operation is defined, and this may be a flat top tool (also called right cutter) or a spherical cutter. In this field, the programmer can choose a tool that is integrated into the database of this software. This database contains some associated cutting parameters that will automatically fill the fields 6, 7 and 8. If the tool to be used does not exist in the database, it can be entered manually. For this, the operator has to fill in the fields 4, 6, 7 and 8 manually.

In 5 the cutting direction relative to the steel tool, i.e., the tool cuts in favour or against the material is indicated. In this field, it can also be set if the machining is spiral, zigzag or in oneway. Generally, the cutting direction is more favorable against the material (the tool is positioned to the left of the material) and with a machining in spiral, to be smooth and continuous.

In 6, the cutting parameters related to the rotation and cutting feed that the tool will perform when implementing the programme in the CNC are set.

Point 7 corresponds to the desired tolerance for the strategy set. The stock allowance in the machining operations is defined, the tolerance of the machining mesh, radial increment (side step) and axial increment (Z) to leave in the area to be machined. The higher the desired quality in the area to be machined, the lower the value of tolerance of the machining mesh.

In 8 the ways to initiate and complete the toolpath are indicated. The programmer has different options in the definition of the input: the entry angle can be smooth (tangential - preferred) or perpendicular to the steel (inadvisable, due to shear forces and the impact of the tool in the steel).

In 9 it must be checked whether there is a possibility of the tool, cone and machine head coming into collision with steel, that is to say, the field where it is possible to automatically obtain the required height of the tool so that no element collides with the steel. In the program the intended can be selected and the software ensures that none of these elements collides with the workpiece, removing them from this. In certain strategies and operations filling this field does not make sense, either because it is a case of high tools (height/diameter ratio exceeding 5; Weinert, Enselmann e Friedhoff

(1997)) or because it is a case of open surfaces. The entry of the tool in certain areas/boxes can also be limited, as it is too close to the tool in question. There are also specific subfields to general reroughing and planes.

In 10 the height of the crest left between the side passages of the tool is defined. During the machining phase, the crests can be tolerated or not. In roughing a high rate of material removal is intended, so the crests can be high, because they are not important. In the finishing phase, there cannot be any crests, thus attributing one of the characteristics to the finishing of a mould (surface quality).

In 11 the smoothing of the corner rays that can be entered in the NC program is defined so that the tool makes soft passages along the rays, not sacrificing the piece. Where the tool radius is greater than the radius of the piece, this option is always to fill with rays which are greater than the ones of the tool. Thus, the tool does not vibrate upon reaching the maximum point of the piece corner radius, which those not leave marks and increases the quality of machining.

After entering all the inputs for the creation of the NC program in the compilation window, the programmer can give the order for the "calculation" to be made, a process that is performed internally. The resulting output can and should be viewed by the programmer in order to visually verify and validate the path made by the tool. If the toolpath does not match the intended one, the programmer will have to make adjustments as are deemed appropriate.

After validation of all previous steps, the programmer converts the program created in WorkNC into machine language (NC), through a processor (integrated in all software programming). Then a name is assigned to the program, which will be forwarded to the corresponding CNC machine tool, so it can be executed.

Figure 12 presents the framework for the creation of programs in WorkNC software, which allows the description presented to be viewed.

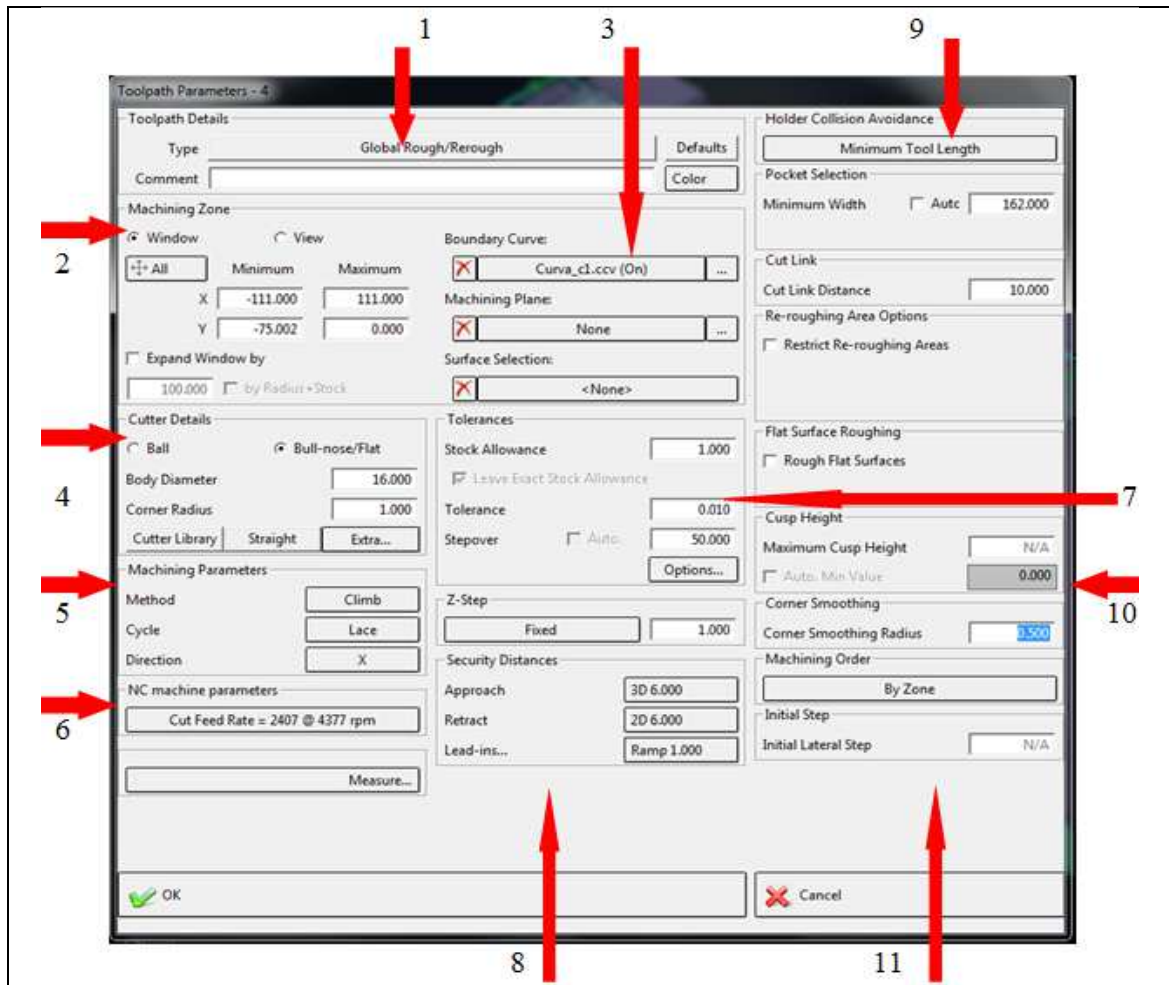


Figure 12 – Compilation window of the program WorkNC

Resulting from the study (own source)

8.12 Internal validity and external validity

“Validity is a control element that is applied particularly in experimental studies” because it *“is what constitutes the essential quality of a study”* (Fortin e Filion, 2006:226). Thus, the validity is directly related to the research and the relationship between variables. This experimental validation may be internal and/or external depending on the origin and purpose of the study. In this case it is intended that the study has internal and external validity.

Internal validity (Cano, 2004) or character of certainty (Tuckman, 2000) is the degree of certainty that the effect on the DV (running times) was caused solely by the IV (types of machining) of the experiment. In other words, it is sure that it was the cause investigated, and no other factor, that produced the observed effects. Tuckman

(2000:173) supports this idea and adds "*that differences occurring as a result of the experimental treatment*" and not derived from any other source, such as the case of VE.

When confidence in the causal inference is high, it is considered that the study has high internal validity. When it is not certain what caused the change (or stability) in the DV, it is considered that it has a low internal validity, the causal inference between cause (IV) and effect (DV) (Cano, 2004) being understood as internal validity. Cano (2004) also notes that the external validity indicates to what extent the proposed causal relationship can be generalized to other moments, and/or other ways to measure the variables in question. This means that if the relationship between the study variables is generalized to other contexts, and/or other ways to measure the variables in question. This means that if the relationship between the study variables is generalized to other contexts and / or ways to operationalize the variables, the study has high external validity. When the causal inference, even if it is clear and unambiguous, cannot be extended to other contexts due to their specific context, it is concluded that the study has a low external validity.

Some authors consider that the internal validity is a condition *sine qua non* of the scientific study but this fact does not justify giving absolute priority to internal validity at the expense of the external one, since this also contributes to the usefulness of the investigation (Kampbel e Standley, 1963)¹⁵. According to Cano (2004), one of the conventional ways of raising the internal validity is to increase experimental control: better control of the experimental context, equating or measuring all the variables that might be an alternative explanation for the causal line proposal.

Thus, procedures were adopted with the aim of creating a study with high internal validity, i.e. ensure that the DV results solely from the IV, and a high external validity (generalizing these findings for all the PMI for plastic injection). Therefore, in this study various techniques will be used to ensure its validity, namely:

- control of the experimental context: all data will be inserted by the investigator, in order to counteract any external influence (human factor or other) on the results;
- the measurement of the dependent variable is through the simulation processes;

¹⁵ in Cano, 2004

- determination of moderating variables (dimension of the mould, moulding zone, among others), since they may be factors influencing the relationship between the IV (types of machining) and the DV (machining time).

PART III

In the third part, the results relating to the time differences between conventional and sustainable simulations (simulation proposed in this dissertation) regarding the process of the milling and of resources (human, energetic and environmental) will be analyzed and discussed and will be discussed the implications for academic knowledge and management. The limitations of the study and some suggestions for future studies will also be set out.

9 ANALYSIS AND DISCUSSION OF RESULTS

In the present study, values of cutting more optimized/sustainable (see Table 8) parameters for milling in the adjustment zones in mould cavities and cores for plastic injection were found, in order to make the productive process and the business more economically, environmentally and socially sustainable.

The choice of simulation as a technique for data collection allowed toolpaths in moulds produced during the year 2010 in the company where the study took place to be created, not only making it possible to compare results (measurement of simulation times), as the elimination of some moderating variables and many external variables to the simulation process, such as times setups (inserting the piece into the machine and removing it, exchanging and calibration of tools, calling programs and other unplanned downtime) and 'dead' times inherent in machining operations that are not accounted for when performing the simulations.

9.1 Milling

As previously mentioned, this study focuses on the adjustment part areas of the piece (cavity and core), by the investigator who made simulation programs for these areas without changing the machining operation in the moulding areas, maintaining the quality of the finish. After defining which cutting parameters are conventional or sustainable (see Table 8) to be used in the milling process, the programs in the WorkNc software were developed which allowed simulation times (of conventional and sustainable milling) shown in Table 9 to be obtained, as well as the respective time

differences (for more detailed analysis, see Appendix 1). Despite all the moulds population being indicated (with respective cavity and core) and organized by strata according to the tonnage (see Table 6), only those that constitute the stratified random sample (comprising 36 moulds, i.e., 36 cavities and respective cores, for a total of 72 pieces) have an indication of the simulations. As previously mentioned, a sequential number was attributed to the moulds of the sample, 1C being the number of the cavity of mould 1 and 1B being the core from the same mould.

The table in Appendix 1 also includes the unprojected area of the surface of the piece covered by the tool in simulation. The values presented are expressed in square millimetres (mm^2), as this is the unit used in the moulds industry in Portugal. This information, although not directly related to the measurement of DV, is an important MV since it may be reflected in some measurements.

In preparing any simulation, the programmer has to make a critical analysis, evaluating whether it is possible to maximize (see Procedures), and how much, the values of radial and axial increment according to the piece to be milled. Thus, the needed minimum quality of the milling remains in the adjustment zones, in order to ensure a correct adjustment of the mould and a significant reduction of assembly time (section of countertop).

The results, summarized in Table 9, show that all sustainable simulation times were lower than those of conventional simulation. In the cavities, the conventional simulation was carried out in 667h37min while the sustainable one was performed in 497h43min, resulting in a difference of 169h54min. Concerning the simulation of cores, the conventional method was carried out in 756h57min compared to the 553h02min of the sustainable method, resulting in a differential of 202h55min.

Simulation times of sustainable milling of cavities and cores represent a saving of 74,56% and 73,17% respectively, which is in line with the results obtained by Tekniker (the machining of high performance allows a reduction of times in the order of 80% when compared with the conventional), since, when using sustainable milling an average reduction of times in the order of 73,87% is obtained; which can be translated into 46,6 days of effective work. Considering that the working hours of each Portuguese collaborator is 8 hours daily and, on average, 22 days of effective work per month, the time indicated above is about 2 months and 5 days of effective work (see Table 9).

Table 9 – Synthesis of the times of the simulations performed

Factors	Cavities		Cores		Totals
	Conventional	Sustainable	Conventional	Sustainable	
Subtotals (hh:mm)	667:37	497:43	756:57	553:02	---
Times (hh:mm)	169:54		202:55		372:47
%	74,56		73,17		73,87
Effective days	---		---		46,6
Effective months	---		---		2,12

Resulting from the study (own source)

It is essential to emphasize that the 2,12 months may still contribute to the timely delivery of moulds, meeting the needs of customers and opening up the possibilities of gaining new customers, increasing the annual production, and enhancing the prestige and competitiveness of the company.

Based on the study results for the sample of 36 moulds (see Table 7) the standard deviation value of the population from the standard deviation value of the sample was estimated, in order to calculate an estimate for the level of accuracy of the results of simulation time differences. In order to raise the level of confidence, the investigator worked with a degree of 95% and used the formula presented by Daniel and Terrell (1995), as expressed in Equation 4 (in Sample).

Erro! A origem da referência não foi encontrada. Since the study conducted utilizes 36 moulds constituted by the respective cavities and cores, an estimate for the execution times of both, from Equation 4 is presented.

Based on the sample, the calculation of the estimate for the standard deviation (σ) of the cavities enabled the value of 5,87857 hours to be reached, while for the cores the value is 6,60023 hours. Thus, the accuracy of the estimate of the differences of simulation times will be performed on the cavities and cores, such as expressed below:

$$d_{cavities} = 1,96 \cdot \frac{5,87857}{\sqrt{36}} \cdot \sqrt{\frac{56-36}{56-1}} \approx 1,16h, \text{ and}$$

$$d_{cores} = 1,96 \cdot \frac{6,60023}{\sqrt{36}} \cdot \sqrt{\frac{56-36}{56-1}} \approx 1,3h$$

Thus, it can be said with a confidence level of 95%, that the results presented will have an accuracy level of the estimate of the differences of simulation times (deviation or maximum error of the estimate of the observed time observed in relation to what would be obtained in a population of 56 moulds) of 1,16 h (i.e. 1h09min) to the cavities and 1,3 hours (i.e. 1h18min) for the cores.

According to the above, it can be concluded that the increase of the cutting parameters (Procedures), collected in the indications for use of the software, CNC programmers and operators (see Table 8), and have been applied in simulation operations in copy and by levels (Z) on this study contributed to the difference of times obtained from the simulations. Thus, from the results shown in the table in Appendix 1, it follows that the greater the increase of the tool (see Table 8), the shorter simulation times and consequently of the milling are.

We also observe that the larger the conventional simulation times, the greater the time differences regarding sustainable strategy. Thus, there is a fluctuation average of 2 to 4 hours, up to the level 2 to 5 Tons, but above that strata (5 to 20 Tons) the differences are greater, going from 11 to 18 hours.

The data in the table in Appendix 1 show that, in general, the simulation times increase with the dimension (tonnage) of the mould since a larger mould will have a greater unprojected area (moulding and adjustment zones), increasing the area that the tool will have to follow in order for the whole surface to be machined. It is therefore natural that the machining times (conventional and sustainable) increase as the strata are composed of larger moulds.

However, it can be seen in Table 10 that the size of the adjustment area to be machined is not directly related to the tonnage of the mould, since, in general terms, there are small tonnage moulds but with a large unprojected area (e.g. mould 1) and large tonnage moulds with a lower unprojected area (e.g. mould 25). At the level of the strata, it can be verified that there are moulds of lower tonnage, of which the adjustment zone to be machined is greater than the one on moulds of higher tonnage (e.g. mould 23 vs

mould 33); moulds of the same dimensional stratum (tonnage) but with dissimilar areas (e.g. mould 1 vs mould 2) and finally moulds of different dimensional strata that have approximate areas (e.g. mould 11 vs mould 25). It is noted that, in the same mould, as in the example of mould 20, the difference in undesigned areas (cavity and core) may be large, which does not always occur (e.g. mould 3).

Table 10 – Example of differences between areas not projected intra strata and among strata

Dimension (tonne - Ton)		Identification		Unprojected areas (mm ²)	
		Cavities	Cores	Cavities	Cores
]0 ; 0,25]	0.140	1C	1B	271315	145204
	0.220	2C	2B	33452	84728
]0,25 ; 0,75]	0.300	3C	3B	21084	21316
]0,75 ; 2]	1.070	11C	11B	97584	79053
	1.900	20C	20B	176589	63088
]2 ; 5]	2.920	23C	23B	394535	567709
	3.300	25C	25B	63294	97104
	4.470	27C	27B	176680	209732
]10 ; 20]	14.340	33C	33B	264456	368571

Resulting from the study (own source)

In view of the above, it is possible to conclude that the geometry of the piece (consisting of the cavity and the core), considered a MV, is an important element for machining and allows the study to be applied to moulds of different tonnages. Thus, relatively simple pieces may have a complex demolding and the opposite can also happen, which leads to another important factor: the complexity of the unprojected area.

It is important to note that the geometric complexity of the moulding zone is not directly related to the scaling (tonnage) of the mould, because, according to Table 5 (Rodrigues, 2002), moulds with a large and very large scale may have an average complexity (as is the case of the gardening industry), very small and small moulds may have a high

complexity (as is the case of the electrical industry/electronics) and moulds with an average size may have an average complexity (as is the case of the domestic utilities industry), that is to say, a mould of any tonnage may have any level of complexity (low, medium or high) (Rodrigues, 2002).

According to the above, the time differences between conventional and sustained simulations are not only justified by the size of the moulds but also by the size and complexity of the unprojected areas, that is to say, the larger and/or more complex the unprojected area of the piece to simulate/program is, the greater the simulation time and hence the machining, regardless of tonnage.

The complexity of the unprojected area explains that moulds with upper areas, compared to others, could have lower simulation times (e.g. moulds 27B vs 1B), or that moulds with unprojected areas of different dimensions could have very similar simulation times (e.g. moulds 1C vs 8C; moulds 4C vs 14C). These peculiarities may be due to the fact that they are less complex moulds in technical terms, i.e., have flatter areas that do not oblige the tool to follow several routes, changes of direction, progress/speed, among others.

9.2 Economic use of resources

The reduction in simulation times, and hence in the production times, enabled what effect the use of sustainable milling in terms of skilled manpower, in energy consumption (monetarily translated into euros) and in the emission of carbon dioxide (CO₂) to the atmosphere (translated in kilograms) to be determined.

9.2.1 Human resources: cost of time man-machine

In the company where the study was conducted, the average price of man/machine time in the machines where the machinations of cavities and cores will be made is 30€/h. With the reduction of hours of simulation, this also reduces execution time, which implies fewer hours of the operator on a certain piece. As a result of the decreased time in the milling of the pieces, the company can add value to the product by reducing the production costs, while maintaining the final quality. Thus, Equation 5 was constructed

using the price of man/machine time in the company concerned and the differences of simulation times, as given in the table in Annex 2 to calculate the " man/machine economy".

Equation 5 – Man/machine economy resulting from simulation differences

$$\begin{aligned} \text{Man/machine economy (€)} &= \\ &= \text{Difference of simulation times (h)} \\ &\quad * \text{average price of the man/machine hour (€/h)} \end{aligned}$$

The results calculated by Equation 5 (summarized in Table 11) show that previously registered reductions of times using the sustainable simulation, enable a total saving of 11,184 € in manual labour used (man/machine hours) to be made (for more detailed analysis, see Appendix 1).

Table 11 – Summary of savings in human resources due to sustainable simulation

Piece		Quantity of pieces	Differences of simulation times (hh:mm)	Simulation times (hh)	Man/machine economy (€)
n°	type				
TOTAL	C	36	169:54	169,89	11.184
	B	36	202:55	202,91	
		72	372:49	372,8	

Resulting from the study (own source)

9.2.2 Energy Resources

To find the values for the "energy economy (€)" (see the summary in Table 13), the value of "average consumption of CNC (kW)" (see Table 12) was calculated, using the theoretical consumption (catalogue) in kilowatts (kW) of such equipment, because it is impossible to predict in which equipment could be used for the simulation done in WorkNC bearing in mind that not all machines have the same energy consumption.

Thus, it is possible to minimize the effects of fluctuations in equipment consumption (moderating variables), contributing to a greater validity (internal and external). Table 12 shows the number of machines and the respective power catalogue, that the researcher also considers as a moderating variable (MV).

Table 12 – Average consumption of CNC (kW)

Equipment	Machine Power (kW)
Moriseiki - SV 500	50
Anayak - VH 3000 Plus	43
Huron - KX 30	54
Anayak - P 3200	40
Anayak - H 3000 MG	50
Mori Seiki - NV 6000	36
HURON - Kx10Five	63
HURON - Nx40	54
HURON - Kx20	54
AVERAGE	49,33(3)

Own source

From the time difference and the average consumption of CNC, the average energy consumption for each simulation was obtained. Thus, the following calculation was performed:

Equation 6 – Average energy consumption in the simulation (kWh)

$$\begin{aligned}
 \text{Average energy consumption in the simulation (kWh)} &= \\
 &= \text{Average consumption CNC (kW)} \\
 &\quad * \text{Difference of simulation times (h)}
 \end{aligned}$$

The calculation of energy savings (€) from the time difference between conventional milling and sustainable milling (see Equation 7) in the several simulations results of the values from Equation 6 (presented in strata in the table of Appendix 3) and the unit value per kWh:

Equation 7 – Energy savings (€) from the time differences of simulations

$$\begin{aligned}
 \text{Energy economy (€)} &= \\
 &= \text{Average energy consumption in the simulation (kWh)} \\
 & * \text{Unit value by kWh(€)}
 \end{aligned}$$

Thus, in 2010, the year in which this study took place, the unit price per kWh applied to the company by the EDP (Energias de Portugal) was 0,11 € (eleven cents) and from the conversion of sustainable milling times constants on the Table 9, for kilowatt (kW), hours (h) and euros (€), it was established that, through the use of sustainable milling, the company could save 2.022,92€ in power, maintaining the level of production (see Table 13) (for more detailed analysis see Appendix 3).

Table 13 – Summary of energy savings using the sustainable simulation

Piece		Quantity of pieces	Simulation time (hh)	Average consumption in the simulation (kWh)	Energy savings (€)
n°	type				
TOTAL	C	36	169,89	18.390,22	2.022,92
	B	36	202,91		
		72	372,8		

Resulting from the study (own source)

9.2.3 Environmental resources: emissions of carbon dioxide (CO₂)

With the average value of energy consumption obtained through simulation (kWh) (see Equation 6), the average amount of carbon dioxide (CO₂) whose emission into the atmosphere can be avoided by saving energy, can be calculated. To this end, the value provided by the official website of EDP on the internet (<http://www.edpsu.pt/pt/origemdaenergia/Pages/OrigensdaEnergia.aspx>, consulted on January 24, 2011) will be used, which indicates that the average emission of carbon dioxide (CO₂) in 2010 was 226,74 g/kWh. This amount includes all the features of energy production, such as hydro, wind, nuclear, cogeneration and microgeneration, as well as from the burning of coal, fuel oil, natural gas and other forms of energy with lower expression not mentioned on the site.

Table 14 (summarized table in Appendix 3) indicates the amount of carbon dioxide (CO₂) not emitted in to the atmosphere because of the difference in machining times by piece. The values presented are expressed in the IS (International System) unit, gram (g), but for better understanding was converted to kilograms, kg. In Table 14 it can be seen that, using the sustainable simulation, the company reduces the emission of carbon dioxide, (CO₂) into the atmosphere over 4 tonnes, which corresponds to 226,74 g / kWh, since less energy was consumed (see Table 13). According to NIE (2010) there is progress in the environmental performance of Portuguese industry, including the emissions of greenhouse gases. Regarding the PMI, it is important to stress that sustainable milling may increase the reduction of greenhouse gases emission, in particular CO₂, since

“in 2008, it is estimated that there has been a decrease in the intensity of emissions of greenhouse gases by 2.1% compared to 2007. In fact, while in 2007, 579,4 g de CO₂ per euro of VAB generated were emitted, in 2008 the value was 567.1 g of CO₂, reinforcing the trend recorded since 2006, of a smaller relative variation of these emissions, compared with the growth of economic activity” (NIS, 2010:1).

In this sense, the company contribute to solving a global problem (in accordance with the one previously stated by the UN, 2011a), while improving their image amongst consumers/customers by assuming a position of responsibility in relation to their environmental impact (Ferreira, 2010).

Table 14 – Summary of the amount of carbon dioxide (CO₂) not emitted in to the atmosphere using the sustainable simulation

Piece		Quantity of pieces	Simulation time (hh)	Average consumption in the simulation (kWh)	CO ₂ (Kg) not emitted
n°	type				
TOTAL	C	36	169,89	18.390,22	4.169,79
	B	36	202,91		
		72	372,8		

Resulting from the study (own source)

Table 15 presents a summary of all the results obtained in this investigation resorting to sustainable simulation in detriment of the conventional one.

This research demonstrates that the use of sustainable milling at the expense of the conventional form reduces the simulation time by 372:49 hours, which corresponds to 46,6 days (about 2 months and 5 days) of effective service and 11.184€ in man /machine hours. Note also that by adopting this type of milling, the company would stop consuming 18.390,22 kWh of energy meaning a direct fit of 2.022,92€. Thus, it can be said that the adoption of simulation/sustainable milling would represent a saving of 13.206,92€ per year for the sample.

In addition to the direct monetary gains for the company, the reduction of milling time can be an indirect gain for the organization, translated into customer loyalty, delivery of moulds within agreed or shorter deadlines (competitiveness), in the production of more moulds with the same resources, among other aspects. On the other hand, the emission of over 4 tonnes of carbon dioxide (CO₂) in to the atmosphere is avoided, contributing to the reduction of the company's environmental impact, improving its image among stakeholders.

Thus, the optimization of the milling process and the consequent reduction of the times used, is important for saving the use of human and energetic resources and the contribution to the competitive potential of the company and its environmental sustainability.

Table 15 – Summary of research results

Dimension (Tonne)	Size sample	Difference simulation times		Average consumption in the simulation (kWh)	Economy of man/machine (€)	Energy savings (€)	CO ₂ not emitted to the atmosphere		Total Savings (€)
		(h)	(days)				(g)	(Kg)	
]0 ; 0,25]	2	9:09	1,14	451,37	274,50	49,65	102343,52	102,34	324,15
]0,25 ; 0,75]	4	8:41	1,08	427,69	260,10	47,05	96974,68	96,97	307,15
]0,75 ; 2]	15	51:36	6,45	2544,93	1547,70	279,94	577038,48	577,04	1827,64
]2 ; 5]	6	54:51	6,86	2705,75	1645,50	297,63	613501,87	613,50	1943,13
]5 ; 10]	5	123:03	15,38	6070,06	3691,50	667,71	1376324,61	1376,32	4359,21
]10 ; 20]	2	45:55	5,74	2265,23	1377,60	249,18	513619,08	513,62	1626,78
]20 ; ∞[	2	79:34	9,95	3925,19	2387,10	431,77	889997,15	890,00	2818,87
Total	36	372:49	46,60	18.390,22	11.184,00	2.022,92	4.169.799,39	4.169,79	13.206,92

Resulting from the study (own source)

10 CONCLUSIONS

This study had as its key point the optimization of the milling process and its contribution to sustainability. The choice made is due to the fact that, on the one hand, milling is considered the 'heart' of the company's production process of moulds, because almost all pieces pass through this section and, the other hand, it is crucial to improve the competitiveness of enterprises, contributing to their economic and environmental sustainability.

To test to test the hypotheses that guide the research and in the impossibility of manufacturing the moulds, computer simulations were performed by using a software program to generate machining paths (WorkNc), commonly used by the PMI in manufacturing moulds for plastic injection. These simulations are focused on the adjustment areas of the cavities and cores of the mould in order to reduce production times. Thus, the moulding parts (core mould) are not affected in this study, which implies maintaining the quality of surface finish, as is currently done.

The study population includes moulds of various sizes, arranged in strata, according to the scale of Rodrigues (2002:169), in order to give wider coverage to the study, since the PMI for plastic injection consists of companies specialized in moulds of various sizes (tonnage). Of the moulds population (56), a random stratified sample of 36 moulds was constituted, making a total of 72 pieces (36 cavities and respective cores), because this type of sampling allows that the elements of all classes have equal probability of being in the sample, enhancing its representativeness (Fortin e Filion, 2006).

From the perspective of the experimental study, variables namely the independent variable (IV) (conventional and sustainable simulations) and the dependent variable (DV) (simulation time) were defined. However, in experimental investigations the investigator must control other variables so that they do not influence the final result, thus moderating variables (MV) (dimensions of the mould) have been adequately controlled and the effect of external variables (EV) was neutralized. This ensures that the results obtained (DV, i.e. simulation times) are only influenced by the IV (type of milling). In this way, only the axial (operation level Z) and radial increments (copy operation) were changed, depending on the type of operation to be performed, and no other technical parameter was changed in programming, in order to neutralize any influence on the results other than the IV. By doing so, the investigator ensured the

internal validity of the study and allowed the comparison of results between the control group (pieces subjected to conventional simulation) and the experimental group (pieces subjected to sustainable simulation).

From the results obtained, it can be seen that the sustainable milling contributes significantly to reducing the simulation times and accordingly the production times (H1), which allows the man-machine time (H2) and the consumption of electricity (H3) to be lowered, which, in turn, leads to a reduction in CO₂ emissions in to the atmosphere (H4). The results obtained show that it is possible to maintain the quality of the produced moulds and reduce delivery times to customers (El-Haggar, 2007), while moderating the use and consumption of resources (UN, 2011a) contributing to the economic and environmental sustainability of the company.

The reduction in the milling times occurs in all segments since the sustainable strategy can be applied to moulds of different tonnages (H5). In this process it was found that the unprojected area of the adjustment zone influences the times of the production process (H6) and to this fact it is possible to add the complexity of the joint line (which defines the unprojected area of the cavity and core), because it also contributes to the observed time difference. Consequently, the time difference is influenced by the unprojected area, by the complexity of the joint line and by the tonnage of the mould, whereby the sustainable strategy could enable a decrease in the milling times in moulds of different tonnages to be achieved.

In view of the above, it is also important to note that the strategy of sustainable milling allows not only the savings through optimal use of human and energetic resources, such as encouraging the development of the company, as there was a decrease in the times of the sustainable milling relative to the conventional form and, consequently, the need for manual labour to be used, as well as in energy consumption and emissions of carbon dioxide (CO₂), as is summarized in Table 15. Following Young (2007) and El-Haggar (2007), companies profit from sustainability, on an economic level (reduction of production time, which is reflected in the man/machine hours and electricity consumption) and environmental level (reducing electricity consumption implies reduced production and consequent emission of CO₂ into the atmosphere).

At the end of the research process, it is clear that, despite the moulds having different tonnages, the increase of axial and radial increments in the simulation program

(sustainable milling) allows for better times in the production process of moulds for plastic injection. Effectively, the guidance for sustainable practices allows the company to create a competitive advantage by producing moulds in less time and with fewer resources, since it allows other variables in the negotiation with customers and opens the possibility to seek new market niches. In short, the adoption of more environmentally friendly forms of production can increase productivity and competitiveness, due to an improved company image in the market, to the reduction of costs and a decrease in the environmental impact (Melo, 2006; Young, 2007).

As noted by Ferreira (2010), the adoption of solutions that contribute to sustainability implies a long-term perspective, optimization and efficiency, interdependence and cooperation allowing, as Young (2007) and Ferreira (2010) advocate, the company's competitiveness in the medium/long term to be improved. Epstein (2008) and the UN (2011b) reinforce the idea and adds that companies that develop strategies to address the shortage of energy resources, the need for manpower and consumables will gain competitiveness. In this context, companies gain a leading role in their economic and environmental sustainability, as well as in the preservation of nature, taking an active role in sustainable development.

10.1 Implications for academic knowledge

This research contributes to academic knowledge since there are no similar studies on the moulds sector, when reviewing the literature in this dissertation, which makes this study an asset for academic knowledge. Thus, the simulation of a sustainable way to operate the milling provide data relevant to the competitiveness of the Portuguese Moulds Industry and for future studies. The importance of the adaptation of production processes in their various moments, is a strategic factor in industrial predominantly exporting sectors.

Although Jorge (2011) has a similar study in the productive process, concerning the use of resources, this investigation went further, since from the measurement of the simulation times of milling the needs of human resources, energy consumption and consequent CO₂ emissions were calculated, in an unprecedented approach to the production process of moulds in Portugal.

It is also important to note that the transformation in the way how the production processes are organized, without resorting to any additional investments, can be an interesting field of research to enhance enterprise competitiveness.

10.2 Implications for managing

The optimization of the production process is extremely important for the Portuguese Moulds Industry for plastic injection, since it directly interferes with the productive times, company productivity and resources used (human, energy, etc.). If this improvement process does not involve new investments, but only the use of the available resources and nevertheless, provides competitiveness, it can be assumed that the gains are actually significant.

By minimizing production times it is possible to produce more in less time, reduce production costs and thus increase the company's competitiveness at national and international levels (El-Haggar, 2007), because it delivers the final mould more quickly, which adds value to the service provided by the company. Moreover, the suggested measures for the optimization process imply that the company becomes more profitable economically and environmentally sustainable, which could open doors to new business areas and market niches, since the contribution to environmental sustainability can be a

distinguishing feature and an added value for the company's image in relation to its stakeholders. Consequently, optimizing the production process is not only an economic necessity for the PMI as it is crucial for their competitiveness, and this should be understood by the people in management positions as a business strategy and not as a secondary issue.

Due to the above, it is expected that the results of the study will be a contribution to the optimization of the production process in the PMI, since it will improve their competitiveness and contribute to the development of this industry, so important for the country.

10.3 Limitations of the study

This study has some limitations that leave open starting points for future investigations. Although the computer simulation is a huge advantage, minimizing the time of the investigation, it does not involve the materialization of the simulations, which can also be regarded as a disadvantage for the study, as the simulations are not subject to unexpected aspects and are realized in ideal contexts.

The lack of similar studies in the sector of moulds, when reviewing the literature in this dissertation, can be considered a limitation of the study since no previous results exist to compare with those obtained in order to give more validity to the research. On the other hand, the construction and operation of the methodology were made more difficult by the inability of replication.

10.4 Suggestions for future studies

It is suggested that, in the future, investigations replicate this study, but from the simple one-piece construction, with relief, that allows testing operations massively used (simulation by copy and by levels).

It would still be scientifically pertinent that similar studies are carried out in other companies, in order to be able to extend the results to larger moulds, standardize cutting parameters and that used other(s) software(s).

This study may also provide the basis for other to examine moulds, taking into account the tonnage and industry client for which it is intended. It would then be possible to analyze the importance and performance of each one of them, realizing its strategic importance to the PMI.

For all the above, it is obvious that there is still a long way to go to a deeper and systematized knowledge on the subject, but it is hoped that this study has contributed not only to the optimization and sustainability of the PMI, but also to opening up new research paths.

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12 Webgraphy

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APPENDICES

Appendix 1 – Times of simulations performed

Dimension (Tonne)	Sample size	Simulation times (hh:mm)								Unprojected areas (mm ²)		
		Identification		Cavity		Core		Differences				
		Cavity	Core	Conventional	Sustainable	Conventional	Sustainable	Cavity	Core	Cavity	Core	
]0 ; 0,25]	0.140	2	1C	1B	4:43:00	2:58:00	17:21:00	11:12:00	1:45:00	6:09:00	271315	145204
	0.200											
	0.220		2C	2B	2:07:00	1:35:00	1:52:00	1:09:00	0:32:00	0:43:00	33452	84728
]0,25 ; 0,75]	0.300	4	3C	3B	0:43:00	0:25:00	0:50:00	0:29:00	0:18:00	0:21:00	21084	21316
	0.415		4C	4B	5:56:00	4:00:00	5:25:00	3:37:00	1:56:00	1:48:00	33049	86582
	0.430		5C	5B	5:56:00	4:00:00	5:25:00	3:37:00	1:56:00	1:48:00	33049	86582
	0.560		mould cnc lathe									
	0.600		mould cnc lathe									
	0.600		mould cnc lathe									
	0.690		6C	6B	0:46:00	0:32:00	1:29:00	1:09:00	0:14:00	0:20:00	14868	25354
	0.840		7C	7B	2:19:00	1:37:00	5:22:00	3:33:00	0:42:00	1:49:00	56828	63088
]0,75 ; 2]	0.910	15	8C	8B	4:18:00	3:29:00	2:37:00	1:55:00	0:49:00	0:42:00	77747	112530
	0.910											
	0.960		9C	9B	2:49:00	2:13:00	1:40:00	1:11:00	0:36:00	0:29:00	30201	29930
	0.960		10C	10B	2:37:00	2:05:00	1:31:00	1:11:00	0:32:00	0:20:00	30201	29930
	1.070		11C	11B	2:00:00	1:14:00	3:37:00	2:14:00	0:46:00	1:23:00	97584	79053
	1.120											
	1.190											
	1.190											
	1.190		12C	12B	2:58:00	2:26:00	3:08:00	2:09:00	0:32:00	0:59:00	30201	29930
	1.250		13C	13B	2:37:00	1:50:00	4:35:00	3:25:00	0:47:00	1:10:00	56828	63088

Dimension (Tonne)	Sample size	Simulation times (hh:mm)								Unprojected areas (mm ²)	
		Identification		Cavity		Core		Differences			
		Cavity	Core	Conventional	Sustainable	Conventional	Sustainable	Cavity	Core	Cavity	Core
]0,75 ; 2]	1.260										
	1.440	14C	14B	5:21:00	3:06:00	10:47:00	6:12:00	2:15:00	4:35:00	170244	187276
	1.450	15C	15B	2:17:00	1:26:00	6:52:00	4:27:00	0:51:00	2:25:00	87351	131127
	1.480	16C	16B	1:37:00	1:00:00	7:10:00	4:09:00	0:37:00	3:01:00	66024	150875
	1.650	18C	18B	6:20:00	3:50:00	9:20:00	5:20:00	2:30:00	4:00:00	144459	210411
	1.670										
	1.695										
	1.695	17C	17B	18:19:00	13:47:00	6:12:00	4:38:00	4:32:00	1:34:00	198148	201131
	1.740										
	1.750	19C	19B	5:48:00	3:33:00	7:48:00	4:29:00	2:15:00	3:19:00	145453	159936
	1.900	20C	20B	7:47:00	5:27:00	9:43:00	6:44:00	2:20:00	2:59:00	176589	63088
	1.905	21C	21B	1:33:00	0:54:00	5:43:00	3:35:00	0:39:00	2:08:00	43333	186797
]2 ; 5]	2.175										
	2.325	22C	22B	9:36:00	6:12:00	11:01:00	8:49:00	3:24:00	2:12:00	130938	166006
	2.920	23C	23B	74:09:00	69:35:00	111:33:00	105:10:00	4:34:00	6:23:00	394535	567709
	2.920	24C	24B	74:09:00	69:35:00	111:33:00	105:10:00	4:34:00	6:23:00	394535	567709
	3.000										
	3.300	25C	25B	5:35:00	4:16:00	6:37:00	4:13:00	1:19:00	2:24:00	63294	97104
	4.190										
	4.205	26C	26B	23:30:00	16:01:00	21:24:00	15:09:00	7:29:00	6:15:00	379527	362374
	4.470	27C	27B	19:45:00	12:30:00	6:27:00	3:48:00	7:15:00	2:39:00	176680	209732

Dimension (Tonne)	Sample size	Identification		Simulation times (hh:mm)						Unprojected areas (mm ²)		
				Cavity		Core		Differences				
		Cavity	Core	Conventional	Sustainable	Conventional	Sustainable	Cavity	Core	Cavity	Core	
]5 ; 10]	5.215											
	5.460	28C	28B	55:42:00	36:49:00	32:58:00	22:36:00	18:53:00	10:22:00	795560	807547	
	5.485	29C	29B	32:46:00	20:58:00	41:26:00	26:21:00	11:48:00	15:05:00	790162	815576	
	5.920	30C	30B	29:09:00	17:58:00	33:23:00	21:31:00	11:11:00	11:52:00	730770	442890	
	7.050											
	7.970											
	8.765	31C	31B	64:41:00	45:42:00	38:29:00	26:46:00	18:59:00	11:43:00	1217278	720812	
	9.055	32C	32B	5:31:00	3:18:00	25:40:00	14:43:00	2:13:00	10:57:00	449437	470262	
]10 ; 20]	14.340	33C	33B	21:31:00	15:57:00	23:39:00	17:10:00	5:34:00	6:29:00	264456	368571	
	15.000											
	15.000	34C	34B	45:02:00	26:55:00	39:10:00	23:25:00	18:07:00	15:45:00	1247391	1161015	
]20 ; ∞]	21.900	35C	35B	48:46:00	41:19:00	69:39:00	42:13:00	7:27:00	27:26:00	1434334	1632046	
	21.900											
	22.000	36C	36B	68:54:00	49:11:00	64:31:00	39:33:00	19:43:00	24:58:00	1047565	1641018	
Total	36			667:37:00	497:43:00	755:57:00	553:02:00	169:54:00	202:55:00			

Own source

Appendix 2 – Savings in human resources due to sustainable simulation

Piece		Quantity of pieces	Differences of simulation time (hh:mm)	Simulation times (hh)	Man/machine economy (€)
n°	type				
1	C	1	1:45	1,75	52,5
	B	1	6:09	6,15	184,5
2	C	1	0:32	0,53	15,9
	B	1	0:43	0,72	21,6
3	C	1	0:18	0,3	9
	B	1	0:21	0,35	10,5
4	C	1	1:56	1,93	57,9
	B	1	1:48	1,8	54
5	C	1	1:56	1,93	57,9
	B	1	1:48	1,8	54
6	C	1	0:14	0,23	6,9
	B	1	0:20	0,33	9,9
7	C	1	0:42	0,7	21
	B	1	1:49	1,82	54,6
8	C	1	0:49	0,82	24,6
	B	1	0:42	0,7	21
9	C	1	0:36	0,6	18
	B	1	0:29	0,48	14,4
10	C	1	0:32	0,53	15,9
	B	1	0:20	0,33	9,9
11	C	1	0:46	0,77	23,1
	B	1	1:23	1,38	41,4
12	C	1	0:32	0,53	15,9
	B	1	0:59	0,98	29,4
13	C	1	0:47	0,78	23,4
	B	1	1:10	1,17	35,1
14	C	1	2:15	2,25	67,5
	B	1	4:35	4,58	137,4
15	C	1	0:51	0,85	25,5
	B	1	2:25	2,42	72,6
16	C	1	0:37	0,62	18,6
	B	1	3:01	3,02	90,6
17	C	1	2:30	2,5	75
	B	1	4:00	4	120
18	C	1	4:32	4,53	135,9
	B	1	1:34	1,57	47,1
19	C	1	2:15	2,25	67,5
	B	1	3:19	3,32	99,6
20	C	1	2:20	2,33	69,9
	B	1	2:59	2,98	89,4

Piece		Quantity of pieces	Differences of simulation time (hh:mm)	Simulation times (hh)	Man/machine economy (€)
n°	type				
21	C	1	0:39	0,65	19,5
	B	1	2:08	2,13	63,9
22	C	1	3:24	3,4	102
	B	1	2:12	2,2	66
23	C	1	4:34	4,57	137,1
	B	1	6:23	6,38	191,4
24	C	1	4:34	4,57	137,1
	B	1	6:23	6,38	191,4
25	C	1	1:19	1,32	39,6
	B	1	2:24	2,4	72
26	C	1	7:29	7,48	224,4
	B	1	6:15	6,25	187,5
27	C	1	7:15	7,25	217,5
	B	1	2:39	2,65	79,5
28	C	1	18:53	18,88	566,4
	B	1	10:22	10,37	311,1
29	C	1	11:48	11,8	354
	B	1	15:05	15,08	452,4
30	C	1	11:11	11,18	335,4
	B	1	11:52	11,87	356,1
31	C	1	18:59	18,98	569,4
	B	1	11:43	11,72	351,6
32	C	1	2:13	2,22	66,6
	B	1	10:57	10,95	328,5
33	C	1	5:34	5,57	167,1
	B	1	6:29	6,48	194,4
34	C	1	18:07	18,12	543,6
	B	1	15:45	15,75	472,5
35	C	1	7:27	7,45	223,5
	B	1	27:26	27,43	822,9
36	C	1	19:43	19,72	591,6
	B	1	24:58	24,97	749,1
Total	C	36	169:54	169,89	11.184
	B	36	202:55	202,91	
		72	372:49	372,8	

Own source

Appendix 3 – Energy savings and the amount of carbon dioxide (CO₂) not emitted to the atmosphere due to sustainable simulation

Piece		Quantity of pieces	Simulation times (hh)	CNC's average consumption (kW)	Simulation average consumption (kWh)	Economy savings (€)	CO ₂ not emitted to the atmosphere		
n°	type						(g)	(Kg)	
1	C	1	1,75	49,33	86,3275	9,50	19573,9	19,57	
	B	1	6,15		303,3795	33,37	68788,27	68,79	
2	C	1	0,53		26,1449	2,88	5928,09	5,93	
	B	1	0,72		35,5176	3,91	8053,26	8,05	
3	C	1	0,3		49,33	14,799	1,63	3355,53	3,36
	B	1	0,35			17,2655	1,90	3914,78	3,91
4	C	1	1,93	95,2069		10,47	21587,21	21,59	
	B	1	1,8	88,794		9,77	20133,15	20,13	
5	C	1	1,93	95,2069		10,47	21587,21	21,59	
	B	1	1,8	88,794		9,77	20133,15	20,13	
6	C	1	0,23	11,3459		1,25	2572,57	2,57	
	B	1	0,33	16,2789		1,79	3691,08	3,69	
7	C	1	0,7	49,33		34,531	3,80	7829,56	7,83
	B	1	1,82			89,7806	9,88	20356,85	20,36
8	C	1	0,82		40,4506	4,45	9171,77	9,17	
	B	1	0,7		34,531	3,80	7829,56	7,83	
9	C	1	0,6		29,598	3,26	6711,05	6,71	
	B	1	0,48		23,6784	2,60	5368,84	5,37	
10	C	1	0,53		26,1449	2,88	5928,09	5,93	
	B	1	0,33		16,2789	1,79	3691,08	3,69	
11	C	1	0,77		37,9841	4,18	8612,51	8,61	
	B	1	1,38		68,0754	7,49	15435,42	15,44	
12	C	1	0,53		26,1449	2,88	5928,09	5,93	
	B	1	0,98		48,3434	5,32	10961,38	10,96	
13	C	1	0,78		38,4774	4,23	8724,37	8,72	
	B	1	1,17		57,7161	6,35	13086,55	13,09	
14	C	1	2,25		110,9925	12,21	25166,44	25,17	
	B	1	4,58		225,9314	24,85	51227,69	51,23	
15	C	1	0,85		41,9305	4,61	9507,32	9,51	
	B	1	2,42		119,3786	13,13	27067,9	27,07	
16	C	1	0,62		30,5846	3,36	6934,75	6,93	
	B	1	3,02		148,9766	16,39	33778,95	33,78	
17	C	1	2,5	123,325	13,57	27962,71	27,96		
	B	1	4	197,32	21,71	44740,34	44,74		
18	C	1	4,53	223,4649	24,58	50668,43	50,67		
	B	1	1,57	77,4481	8,52	17560,58	17,56		
19	C	1	2,25	110,9925	12,21	25166,44	25,17		
	B	1	3,32	163,7756	18,02	37134,48	37,13		
20	C	1	2,33	114,9389	12,64	26061,25	26,06		
	B	1	2,98	147,0034	16,17	33331,55	33,33		

Piece		Quantity of pieces	Simulation times (hh)	CNC's average consumption (kW)	Simulation average consumption (kWh)	Economy savings (€)	CO ₂ not emitted to the atmosphere	
n°	type						n°	type
21	C	1	0,65	49,33	32,0645	3,53	7270,3	7,27
	B	1	2,13		105,0729	11,56	23824,23	23,82
22	C	1	3,4	49,33	167,722	18,45	38029,29	38,03
	B	1	2,2		108,526	11,94	24607,19	24,61
23	C	1	4,57		225,4381	24,80	51115,83	51,12
	B	1	6,38		314,7254	34,62	71360,84	71,36
24	C	1	4,57		225,4381	24,80	51115,83	51,12
	B	1	6,38		314,7254	34,62	71360,84	71,36
25	C	1	1,32		65,1156	7,16	14764,31	14,76
	B	1	2,4		118,392	13,02	26844,2	26,84
26	C	1	7,48		368,9884	40,59	83664,43	83,66
	B	1	6,25		308,3125	33,91	69906,78	69,91
27	C	1	7,25		357,6425	39,34	81091,86	81,09
	B	1	2,65		130,7245	14,38	29640,47	29,64
28	C	1	18,88		931,3504	102,45	211174,39	211,17
	B	1	10,37		511,5521	56,27	115989,32	115,99
29	C	1	11,8		582,094	64,03	131983,99	131,98
	B	1	15,08		743,8964	81,83	168671,07	168,67
30	C	1	11,18	551,5094	60,67	125049,24	125,05	
	B	1	11,87	585,5471	64,41	132766,95	132,77	
31	C	1	18,98	936,2834	102,99	212292,9	212,29	
	B	1	11,72	578,1476	63,60	131089,19	131,09	
32	C	1	2,22	109,5126	12,05	24830,89	24,83	
	B	1	10,95	540,1635	59,42	122476,67	122,48	
33	C	1	5,57	274,7681	30,22	62300,92	62,3	
	B	1	6,48	319,6584	35,16	72479,35	72,48	
34	C	1	18,12	893,8596	98,32	202673,73	202,67	
	B	1	15,75	776,9475	85,46	176165,08	176,17	
35	C	1	7,45	367,5085	40,43	83328,88	83,33	
	B	1	27,43	1353,1219	148,84	306806,86	306,81	
36	C	1	19,72	972,7876	107,01	220569,86	220,57	
	B	1	24,97	1231,7701	135,49	279291,55	279,29	
Total	C	36	169,89	---	18.390,22	2.022,92	4.169.799,4	4.169,79
	B	36	202,91					
		72	372,8					

Own source