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FACULDADE DE CIÊNCIAS E TECNOLOGIA
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Dimensionamento e planeamento de lotes de produção numa unidade fabril de injeção plástica

Dissertação apresentada para a obtenção do grau de Mestre em Engenharia e Gestão Industrial

Lot-sizing and production planning in a plastic injection plant

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Dream, the beginnings will seem humble, so prosperous will the future be.

Min Yoongi – “So Far Away”

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Resumo

Motivado por um caso real, este trabalho apresenta a aplicação de modelos de otimização para o dimensionamento e planeamento de lotes de produção numa unidade fabril de injeção de plásticos. Atualmente, qualquer empresa de manufatura necessita de ter em conta as mudanças de mercado e é importante que adotem maneiras de flexibilizar a sua produção de acordo com as necessidades que vão surgindo. Um dos problemas mais discutidos neste âmbito passa pelo uso de modelos matemáticos que auxiliem no planeamento de produção e, mais especificamente, no dimensionamento de lotes produtivos. Este problema é especialmente relevante porque influencia a capacidade efetiva de moldes e máquinas. Assim, segue-se uma abordagem monolítica de dimensionamento dos lotes e planeamento da produção, sugerindo-se uma solução para o processo de tomada de decisão. As características específicas do sistema produtivo em estudo, como máquinas em paralelo, compatibilidade molde-máquina, *setups* e *setup carry-over*, e ainda a existência de *backorders* motivaram a construção dos modelos que visam a redução dos custos de produção, *stock* e de *setup*, bem como a minimização do tempo total gasto em tarefas de *setup*, dado que estas representam um ponto crítico para a empresa e existe uma necessidade inerente de otimização das mesma.. Explora-se ainda a aplicabilidade prática do modelo de dimensionamento de lotes criado e são apresentados alguns desafios relacionados com integração do mesmo no sistema produtivo considerado. São ainda apontadas algumas diretrizes para a sua possível implementação.

Palavras-chave: Planeamento de Produção, Dimensionamento de lotes, Otimização Linear

Abstract

Motivated by a real case, this paper intends to present the application of optimization models for the sizing and planning of production batches in a plastic injection plant. In modern society, any manufacturing company needs to take into account market changes and it is important that they adopt ways to make their production more flexible and suitable for the ever-changing needs. One of the most discussed problems in this field is the use of mathematical models that assist in production planning and, more specifically, in the sizing of productive batches. This problem is especially relevant because it influences the effective ability of molds and machines. Thus, the following is a monolithic approach to a lot-sizing and production planning problem, suggesting a solution to the decision-making process. The specific characteristics of the production system under study, such as parallel machines, mould-machine compatibility, setups and setup carry-overs, and also the existence of backorders motivated the development of models aimed at reducing production, stock and setup costs, as well as minimizing the total time spent on setup tasks, since these represent a critical point to the company and there is an inherent need for optimizing it. It also explores the practical applicability of the developed lot-sizing model, and some challenges related to the integration of this model in the production system are presented. Some guidelines for its possible implementation are also pointed out.

Keywords Production Planning, Lot-sizing, Linear Optimization.

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ABBREVIATIONS

MILP – Mixed Integer Linear Programming

MIP – Mixed Integers Programming

MTS – Make to Stock

MTO – Make to Order

ATO – Assemble to Order

LS-U – Single-item Uncapacitated Lot-Sizing Model

CLSP – Capacitated Lot-Sizing Problem

CLSPL - Capacitated Lot-Sizing Problem with Setup Carry-Over

MRP – Material Requirements Planning

MRP II – Material Requirements Planning II

ERP – Enterprise Resource Planning

MES – Manufacturing Execution System

CIM – Computer Integrated Manufacturing

INTRODUCTION

Production planning is a topic that always had great relevance in the industrial context as well as in the academic fields. It is usually defined as the act of planning the supply of resources and raw materials, as well as the planning of the productive activities required for the processing of materials into finished products, while trying to meet the provided demand in the most effective and economical way possible (Pochet and Wolsey, 2006).

With the rapid increase in the development of new technologies that has been happening in the last few decades and the resulting tendency to adapt to such advances, it becomes essential for companies to make their manufacturing planning systems increasingly efficient and flexible, leading to increased productivity and, consequently, improve the customer satisfaction. The problems deemed of importance in this area influence decisions at various levels, such as the size of productive batches of the different products, the time range in which such batches are to be produced and, also, in which productive resource or plant, when multiple plants are considered, certain product must be produced. When these topics are combined they make what is commonly called, according to Pochet and Wolsey (2006), the lot-sizing problem. Lot-sizing techniques may be applied in production systems in order to determine the optimal timing and level of production, increasing the overall efficiency while fulfilling the customer's needs (Jans and Degraeve, 2008).

Thus, this research is motivated by the need of testing the applicability of a dynamic lot-sizing and production planning model in a practical industrial setting. Although this has been a recurring subject in many published works, there is a constant need for adapting existing models to the specific needs of each individual system. Since most lot-sizing models are very general, in order to provide a global solution for every problem, there are unique variables in each production system that aren't taken into account, making those models inefficient for specific industrial cases. This translates into the need for adapting the existent models to the necessities of each production system.

The approach followed to solve the optimization problem consists in developing a mathematical model as a mixed integer linear programming (MILP), followed by its implementation using a commercial solver, the IBM ILOG CPLEX Optimizer, and using the Microsoft Excel as a visualization and support tool.

The objective of this paper consists primarily in the development of the above-mentioned lot-sizing model for a productive system that uses the plastic injection molding process to produce components, mainly connectors, for the automotive industry. This production planning model must take into account the available capacity of different types of resources as well as the compatibility between the resources and the products. Furthermore, the model must be simple enough so that its application is viable, since most models take a very significant time to compute when applied to industrial-sized planning.

This primary goal leads to some secondary goals based on the results that are expected by the company. In this way, it is intended to achieve, with the implementation of the described model, an improvement in the operational efficiency, either through cost minimization or through better use of available resources (machines, molds, labor, …).

Some of the objectives proposed by the company consist of the decrease of mold and raw material changeovers in the injection machines, since these changes incur setup times for the machines and periods of process stabilization. It is also expected a decrease in the number of products that are delivered to customers after the initially proposed lead-time, increasing the process reliability and, consequently, customer satisfaction.

The document is structured as follows – a brief introduction of the motivation and impact behind this research, which followed by the theoretical framework and the methodology. It continues to the presentation of the practical case study that motivated this work followed by the results and discussion. Finally, some conclusive remarks and suggestions for future research are made.

1. THEORETICAL FRAMEWORK

This work aims to discuss one of the most important problems that exist in the context of industrial manufacturing – the problem of lot-sizing.

It is important to emphasize that, although there is an extensive literature regarding this type of optimization models and its application in the industry, these are mainly focused on time-based performance and comparison between models. The described models rarely end up being tested in a practical way in real industrial environments, with few comparing the results of the models with the results of the planners and even fewer are those addressing problems related to the modelling and implementation phase of optimization methods in the industry. Thus, focusing the research in determining aspects for the integration of these models of optimization in industrial practices, can help to obtain crucial information regarding their improvement (Moniz et al., 2014)

Resulting from this need to integrate more theoretical models in an industrial environment, it is considered essential to explore, in the first phase, other important aspects for understanding the production system in question. These comprise the type of production and inventory policy, which could be applied in manufacturing systems, as well as the information systems that are applied to companies in order to facilitate their production planning. It is also important to make some considerations about the concept of production planning and what it implies.

1.1. Inventory Policy

The resulting inventory profile relies essentially on three different types of strategies. The "make-to-order" (MTO) policy, where the production is initiated after specific customer orders are received, or the "make-to-stock" (MTS) policy that, as the name implies, allows the production of products that are stored until they are necessary. This takes into account demand forecasts, regarding the sales history and other criteria, or it can also be provided by the customers. On the other hand, a third possible strategy goes through the combination of these two methods – “assemble-to-order” (ATO), and it is necessary to define criteria that allows us to perceive in which situations or which products should follow each one. A comparison between these inventory policies was discussed in the work of Popp (1965). The author uses a simplified inventory problem to test the applicability of each of the strategies, whether these are simple, or combined. Considering the elements of the problem the demand (defined by a distribution function), the time-based restrictions (existing lead times), the costs, the optimization criteria and the different policies, it was possible to conclude that the best applicability of a certain strategy depends on the relationship between setup and inventory costs. In short, the combination of the two policies is more advantageous when there are extreme values of demand, that is, in a certain period there may be a high demand for a certain product and, in a subsequent period, the demand decreases to considerably lower values, or vice versa.

1.2. Lot-sizing Models

Since the publication of the work of Harris (1913), the lot-sizing problem has gained a lot of interest, both at an industrial and academic level. Since each production system is a different case, one must always consider the individual characteristics and parameters, never failing to use the experience of production planners. Furthermore, the main factors influencing the determination of the economic dimension of production batches include various types of costs, such as the unit cost of production and the cost of setup (Harris, 1913). The minimal total costs occur when the economic order quantity is realized, and the average setup/ordering cost equals the average holding cost, which is illustrated in Figure 1.1. Large quantity production orders mean an increase in the amount of products that have to be stored, i.e. stock. Warehousing this stock requires significant costs and also a large depreciation.

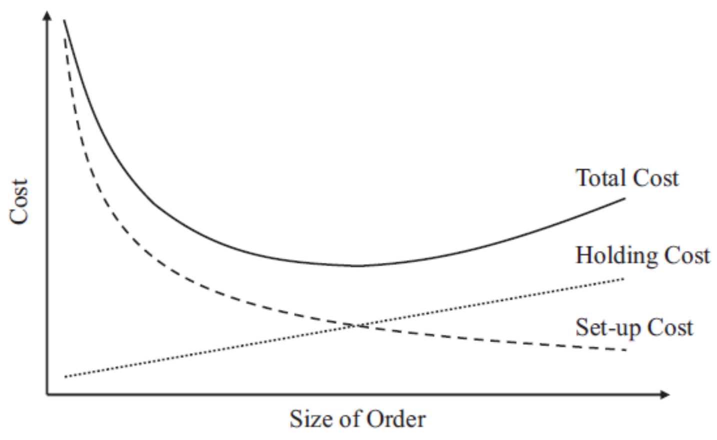

Figure 1.1. Relevant cost curves for Harris' lot size model (as in Glock e al., 2014)

According to the author it is usual to consider this value between 10% and 20% of the stock value. All of these factors allow you to calculate, in general, the unknown factor, that is, the batch size.

A few decades later, this theme is discussed in several works, including the one developed by Wagner and Within (1958) that considers a dynamic version of the economic lot-sizing model.

When the authors consider that the demand in each period is known, but variable, and that the inventory costs also vary between each period, then the so far suggested approaches fail to guarantee a minimum cost solution. Thus, the authors developed an algorithm that allows solving the dynamic version of the model.

None of the aforementioned cases consider available capacity values, thus relating to the simplest production planning model that is known as single-item uncapacitated lot-sizing model (LS-U) (Pochet and Wolsey, 2006). This corresponds to the production planning of a single product without being considered resource capacity constraints, that is, admitting infinite capacity values. However, this model is too simple to be applied in a real production system, resulting in the development of additional models based on this.

Another publication that is important to highlight consists of the work of Manne (1958) that presents a linear programming model for solving the lot-sizing problem with consideration of costs associated with setups and capacity constraints. One of the most important variables is the production breakdown for each individual item so that it can meet the needs of the customers. Batch splitting incur an increase in setup costs, so determining an optimum batch size requires a balance between setup cost reduction and the inherent advantages of a production smoothing over time.

The above-mentioned article highlights the fact that companies do not have unlimited production capacity. They usually also produce more than one product. Therefore, any model that intends to represent, as accurately as possible, the reality of a productive system must consider these issues.

The capacitated lot-sizing problem (CLSP) can be seen as an extension of the lot sizing problem under dynamic demand that considers capacity constraints as well as other important characteristics of the productive systems (Glock et al., 2014). This problem is considered NP-hard, both in the multi-item case and the single-item case, which means that it is impossible to test all the solution in useful computational time (Brahimi et al., 2006). Some extensions to the standard model that are described as follows.

1.2.1. Extensions to the Capacitated Lot-sizing Model

The CLSP can be described as having the objective to find the optimal production plan that minimizes setup and inventory costs and delivers optimal lot-sizes and production periods for multiple products that have a discrete demand volume in predefined periods. This problem has several extensions considered significantly important in the industrial practice. One of these extensions is related to parallel machines. It implies that a product may be produced in any of the parallel machines and this leads to an increase in the planning problem complexity, since it now includes a new decision called the “loading” problem: choosing which machine is going to produce each product and how many machines can be used in parallel to produce the product at the same time in each period (Quadt and Kuhn, 2007). This extension is easily added to the CLSP by augmenting the needed variables with an additional index that represent the individual machines. The works of Dillenberger et al. (1994) and Gopalakrishnan et al. (1995) are examples of the use of this extension.

Another useful characteristic of the planning problems is the inclusion of setup carry-over. This means that the machine is able to carry over its setup state to other periods, while the original CLSP implies a setup each time for each product in each period. If setup carry-over is considered then the last product of each period may be produced in the next period without incurring an additional setup, which is often what happens in many industries (Quadt and Kuhn, 2007). When this extension is considered, the optimal solutions become quite different, and if accounted with the parallel machines extension it may be advantageous to consider a lot-for-lot policy that reduces the number of setups. The best-case scenario would be to have the same product in a certain machine for the whole duration of the planning horizon, needing only one setup to start production (Haase, 1998). To consider setup carry-over in the CLSP some parameters, variables and conditions have to be included, such as a parameter that gives the initial setup state of a certain product at the beginning of the planning interval, a variable that if activated states that the setup state for a certain product is carried over from one period to the next and also the needed changes to the constraints.

The work of Haase (1994) establishes the name CLSPL for a CLSP with setup carry-over and solves a standard CLSPL with a single machine, without back-ordering and without setup time considerations. Another example of the application of the setup carry-over extension is in the work of Suerie and Stadtler (2003) where it is used an approach that covers setup times and multiple machines in a multi-level production environment but don't allow parallel machines or back-ordering.

The last considered extension is back-ordering, which allows a product to be produced after the given demand period but incurs a cost for each period and each unit of the delay. The inclusion of this extension may be crucial for highly capacitated environments and many real production situations since, without it, the plans would almost always turn out with infeasible solutions. More often than not this is a reality in productive systems, so it is crucial to minimize the back-order of products. Back-orders can be included in the CLSP by adding some parameters and variables such as an initial back-order volume of the product at the beginning of the planning interval, the back-order cost for each product and also the decision variable of back-order volume at the end of the considered period. The inventory flow constraints must also be adjusted to consider this new parameters and variables (Quadt and Kuhn, 2007). Several works integrate setup carry-overs in their planning models such as Smith-Daniels and Smith-Daniels (1986) that present a single machine mixed integer programming model with back-orders that combines small bucket and big bucket approaches, and Millar and Yang (1994) that present two different algorithms for a single machine lot-sizing problem with back orders, based on Lagrangian decomposition and relaxation.

1.2.2. Solution Approaches

Since this type of lot-sizing problems are more computationally difficult the larger the problem size is, there was the need to create different approaches that allowed to divide the problem in a set of different smaller subproblems that contained less information and, thus, become easier to solve in a viable computational time.

One of the approaches that can be found in the literature, finds a way to simplify the problem by using a two-phase workcenter-based decomposition scheme that allows to solve industrial-dimensioned problems within reasonable time and accuracy. Since it is known that every N-item uncapacitated problem can be subdivided into N single-item uncapacitated problems (Kirca and Kokten, 1994), in the first stage it solves an aggregated problem for each “part family” which are sets of products with similar characteristics and, in the second stage, it solves the disaggregated problem on a rolling-horizon basis. It is then created a workcenter-based decomposition scheme that decomposes the disaggregated problem into smaller subproblems and generates the final feasible solution (Dastidar and Nagi, 2005).

Another example of this is in the work of Quadt (2004) where it is suggested a hierarchical solution approach that consists of a primary phase of lot-sizing at the bottleneck stage. This approach decomposes the entire production system into separate production stages and plans the bottleneck stage separately form the non-bottleneck stages. These non-bottleneck stages are then considered simultaneously in the next phases that relate to the scheduling part of the approach.

In Quadt (2009) the lot-sizing problem at the bottleneck is addressed and a mixed integer programming model is presented along with a new approach to solve this problem. This planning problem considers some extensions of the CLSP with respect to three additional aspects. First, the products may be delivered later than their demand periods, incurring back-order costs. Secondly, it considers the possibility of carrying over the setup states from one period to the next, since high-volume products may be produced continuously over several adjacent planning periods. Finally, parallel machines are to be considered since the bottleneck stage includes this characteristic and there is the need to choose which and how much machines produce certain product in the considered periods.
These multiple approaches allow to simplify otherwise very complex problems that would take a lot of computational power and time to solve.

1.3. Production Planning

Production planning is usually defined as the process of allocating resources to different productive activities in order to satisfy the customer or forecast demand over a certain planning period in the most efficient and economical way possible (Gelders and Van Wassenhove, 1981).

As a result, production planning goes through a decision-making process to optimize the balance between economic objectives, such as minimizing costs or maximizing profits, and the goal of customer satisfaction, this one being less tangible but equally important

(Pochet and Wolsey, 2006). According to the authors, to achieve these objectives, manufacturing planning systems have become increasingly sophisticated in order to optimize both productivity and flexibility of productive operations. In fact, the need to respond quickly to market and demand changes has created an increase in more refined production planning models that are better able to represent and exploit the flexibility of a productive process, without needing to sacrifice the overall levels of productivity (Pochet and Wolsey, 2006).

Production planning can encompass three different time ranges in the decision-making process (Karimi et al., 2003. The first is long-term planning that usually focus on aggregate needs and involves making decisions at the level of choosing products, machines and processes, facility location and design and even resource planning. Then, there is medium-term production planning that relates to the MRP (Material Requirements Planning), and production related decisions such as production quantities or lot-sizing. This intends to result in minimized overall costs and optimizations of several performance criteria. Finally, the planning can be done short-term when it involves day-to-day decisions such as operation scheduling and job sequencing and control).

In this context of sophisticated and integrated manufacturing systems, production planning models are often based on mixed integer programming models (MIP) (Gelders and Van Wassenhove, 1981). This derives from certain characteristics of problems such as costs and times of setup or startup, resource allocation decisions, among others. The changeover, which relates to setups, is designated as the work carried out to change a certain machine, resource, workstation or line since it has done the last good part A until it is able to produce the first good part B (Cox and Blackstone, 1988). Thus, whenever a new production batch is started, a setup is incurred, which implies time and additional production costs. Therefore, it is necessary to use binary or integer variables to model these characteristics. When it comes to this type of planning models, the difficulty of resolving them can be significantly greater in the case of large data instances, which usually happens in industrial environments. However, several techniques can be used to improve or optimize the mathematical formulations of the models, or to create more efficient optimization algorithms that allow solving the aforementioned models. The use of a suitable heuristic or efficient algorithm may allow to drastically reduce the computational time required to solve this type of models and to achieve solutions that are within certain deviation limits of the optimum solution (Dixon and Silver, 1981).

Usually, these models intend to determine production batches, more specifically their size, and when they are produced, within a certain time interval, or the designated planning horizon and always with the main objective of responding to customer demand.

As previously described, these demand values can derive from forecasts in a make-to-stock environment, from concrete orders when it comes to a make-to-order environment, or even a combination of the two. In addition, there are particularities of the production systems that should be considered when creating the planning model, for example, the availability or capacity of resources (whether these are machines, manpower or subcontracting), the production and inventory costs, among others (Jans and Degraeve, 2008).

1.4. Enterprise Information Systems

The industry's growing global competition, the need to improve production planning and to have better management of productivity and waste has led to the implementation of increasingly developed and flexible tools that help in the decision-making process of manufacturing companies (Ehie and Madsen, 2005).

Therefore, MRP emerged, which means Material Requirements Planning. It allowed to evaluate how much material of a certain type is needed and at what time, by calculating the company's productive needs. Since MRP systems consider the natural dependency between assembly schedules and parts fabrication it contributes in the level of customer service and inventory optimization, bringing a fundamental change in the way manufacturing inventories and material flows were managed (Whybark and Williams, 1976).

The lot-sizing problem is a much-researched topic, particularly in MRP context. Even though the decision-making has to be made despite of the use of an MRP framework, the combination of lot sizing routines with formal MRP procedures gives rise to specific problems and is, therefore, an interesting area of research (Gelders and Wassenhove, 1981). Eventually, the MRP system started to be applied to increasingly encompassing functions

and the term manufacturing resource planning II (MRP-II) was coined in order to identify the newer systems' capabilities that enabled the evaluation of implications associated with future demand, as well as the need of materials (Jacobs and Weston Jr., 2007).
Furthermore, the need for more integrated systems led to the development of the Enterprise Resource Planning (ERP). ERP system software packages are highly complex systems that allow to integrate all the data and processes of an organization into one system and provide easy access to information needed in the decision-making process (Gargeya and Brady, 2005). This integration can be considered in a functional perspective (systems of finance, accounting, human resources, production, marketing, sales, purchases, ...) and, also, under a systemic perspective (transaction processing system, management information systems, decision support systems, ...). Effectively, these systems have now reached a level of maturity that allows major corporations to realize the benefits of incorporating them in their day-to-day processes (Jacobs and Weston Jr., 2007).

One of the most used integrated business management systems in the industry was developed by SAP (Gargeya and Brady, 2005). These systems are based on ERP and help in managing the company as a whole, dividing it into modules, and in which each module corresponds to a specific area. In this way, the ERP systems provide a multitude of benefits to the companies and its implementation should not be viewed as just an IT solution but as a system that could possibly transform the company into a more efficient and effective organization (Ehie and Madsen, 2005).

Another important, and more recent tool is the Manufacturing Execution Systems (MES). It emerged with the rise of the CIM concept (Computer Integrated Manufacturing) and was developed as a combination of various data collection systems that allow for a more integrated management platform and holds three distinct function groups: production, quality and human resources (Kletti, 2007).

2. METHODOLOGY

2.1. Step 1: Descriptive Analysis

In the first of our methodology, we describe the productive system, and all its characteristics. With that in mind, the collected data about products, sales, resources, costs and general production rules were analysed with the purpose of drawing a general picture of the production process. This allows understanding the most important factors to account in the design of the optimization model and, consequently, in its implementation. It also helped in understanding the structure of the data that the model will have to work with, and all it entails.

Factors such as the type of production policy (MTO or MTS), the flow of information within the production planning department and the production lines, time-dependent factors such as the considered lead-times, backorder policy or the inventory management are crucial in helping define the productive process.

Additionally, there are many data analysis tools that can be used in this descriptive analysis, such as the ABC-XYZ analysis that allows to classify products according to their relevance and demand values. These are described below.

- **ABC-XYZ Analysis**

There are many ways to classify items that are manufactured by a company. This process of classification has great importance in the way that assists in the material planning strategy of the different items and supports stock management. One of the main tools that are usually applied is the ABC analysis which classifies products according to its periodic turnover. It is determined as the product of the cost of a unit and its consumption rate within a certain period. Thus, it divides the products in 3 distinct classes (Scholz-Reiter et al., 2012):

- A-items: 0-80 percent of the accumulated consumption value;
- B-items: 80-95 percent of the accumulated consumption value;
- C-items: 95-100 percent of the accumulated consumption value;

Another great tool that can be used as a complementary classification method is the XYZ analysis. It analyses the items' usage regularity and divides them into classes, which are described as follows (Scholz-Reiter et al., 2012):

- X-items: some extent constant consumption, fluctuations are rather rare, coefficient of variation < 0.5;
- Y-items: stronger fluctuations in consumption, usually for trend-moderate or seasonal reason, coefficient of variation between 0.5 and 1;
- Z-items: Completely irregular consumption, coefficient of variation > 1.

One of the advantages of these methods is that the XYZ analysis supports the ABC analysis, which is used as a primary classification tool. Hence the following classification matrix (Table 2.1.) that intends to connect the two:

Table 2.1. ABC-XYZ classes descriptions

	A	**B**	**C**
X	AX Class • High consumption value; • Even demand; • Reliable forecasts.	BX Class • Medium consumption value; • Even demand; • Reliable forecasts.	CX Class • Low consumption value; • Even demand; • Reliable forecasts;
Y	AY Class • High consumption value; • Predictably variable demand; • Less reliable forecasts.	BY Class • Medium consumption value; • Predictably variable demand; • Less reliable forecasts.	CY Class • Low consumption value; • Predictably variable demand; • Less reliable forecasts.
Z	AZ Class • High consumption value; • Sporadic, variable demand; • Forecasting unreliable or impossible;	BZ Class • Medium consumption value; • Sporadic, variable demand; • Forecasting unreliable or impossible;	CZ Class • Low consumption value; • Sporadic, variable demand; • Forecasting unreliable or impossible;

2.2. Step 2: Problem Modelling

There are several aspects that should be considered when choosing the most suitable optimization model to the case in hand. Since these are crucial to the understanding of the modelling process, some of these basic concepts are explained in this section, as defined by Karimi et al. (2003):

- **number of products:** the model can be deemed as a single-item one, when it only considers the production of one product, or multi-item, when it considers more than one end item;
- **number of levels:** production systems may be single-level or multi-level. When considering a single-level system it means that the end item is directly produced from raw or purchased materials with no intermediate subassemblies. Product demand comes directly from customer orders or market forecasts. In multi-level systems the output of an operation is the input of another, which means that raw materials go through several operations to become end products and there is a parent-component relationship among items. Therefore, the demand of one item may be dependent of another;
- **capacity or resource constraints:** one of the most important factors in this type of models is whether it is capacitated or uncapacitated. When there is no restriction on resources the problem is said to be uncapacitated. On the other hand, if capacity restrictions are implied the problem is capacitated which directly affects the problem complexity;
- **demand:** the demand type in an important input to the model. If the demand is static it means that it remains constant but if the demand is dynamic, then its value can change over time. If this demand value is known before the production starts, then it is called deterministic and this means that the company follows a make-to-order policy as described before. On the other hand, if the demand values are based on probabilities and forecasts then it is termed probabilistic. Relating to the single-level or multi-level characteristic the model can have independent demand when an item's requirements does not depend on decisions regarding another item's lot size and this is considered in the single-level models. In the multi-level problems, the demand is

dependent because there is a relationship between the items and the demand at one level depends on the demand for their parent-items;

- **planning horizon:** the planning horizon is defined as the time interval on which the master production schedule extends into the future. If the planning horizon is finite, then it is usually related to dynamic demand and if it is infinite then it considers stationary demand. The system may also be classified as a continuous or discrete-type system, whether it can be observed continuously or at discrete time points. This concept relates to the big-bucket/small-bucket typology of the planning problems, in which big-bucket problems are those where the time period is long enough to produce multiple items, while for small-bucket problems the considered time period is short and so it only allows the production of one item in each time period. When the available data is uncertain then it should be taken into consideration a rolling planning horizon. Using this approach, the solutions obtained for each horizon act as heuristics but cannot guarantee an optimal solution;
- **setups:** if setup costs and/or setup times are considered in the planning problem, they will usually be modelled by introducing binary variables in the mathematical formulation and cause the problem solving to increase in difficulty. In most cases, production changeover between different products may incur a setup time and setup cost. When it is possible to continue the production run from the previous period into the current period without needing an additional setup, thus reducing the setup cost and time, we are in the presence of a system that allows setup carry-over;
- **inventory:** if inventory shortage is allowed then it means that it is possible to satisfy the demand of the current period in future periods (backlogging), or the demand may even not be satisfied at all (lost sales). The combinations of the two is also possible. This usually introduces an additional cost in the objective function.

After taking into consideration all these aspects it is possible to classify the problem in question and choose a suitable model from the literature that allows to have a starting point that can be iteratively developed according to the needs of the production system in hand.

The model presented next was used as a starting point for the final optimization model in this work.

The production planning model, designated as Master Production Schedule (MPS), was created, being designated, in its most simplified form, as multi-item (single level) capacitated lot-sizing model (Pochet and Wolsey, 2006). Its goal is to plan a set of products, usually finished products, over a certain time horizon. In this model it is defined the index i to represent the set of products to be produced, the index k representative of the set of productive resources whose capacity is limited and, finally, the t index relative to the time periods to be considered. The decision variables consist of the variable relative to the productive batches x, the binary variable y, which denotes positive production of a certain product and the stock variable s. In addition, it considers some parameters associated with costs, such as production, setup and inventory costs, and finally the parameter corresponding to the demand. Maximum production limits and available capacity values of the resources are also considered.

The formulation is as follows:

$$\min \sum_i \sum_t (p_t^i x_t^i + q_t^i y_t^i + h_t^i s_t^i) \tag{1}$$

$$s_{t-1}^i + x_t^i = d_t^i + s_t^i \;\; \forall i, t \tag{2}$$

$$x_t^i \leq M_t^i y_t^i \; \forall i, t \tag{3}$$

$$\sum_i \alpha^{ik} x_t^i + \sum_i \beta^{ik} y_t^i \leq L_t^k \; \forall t, k \tag{4}$$

$$x \in \mathbb{R}_+^{mn}, s \in \mathbb{R}_+^{m(n+1)}, y \in \{0,1\}^{mn} \tag{5}$$

$i = products, \quad 1 \leq i \leq m$

$k = resources, \quad 1 \leq k \leq K$

$t = time\ periods, \quad 1 \leq t \leq n$

$p_t^i = unit\ production\ cost\ per\ item\ in\ each\ period$

$q_t^i = fixed\ production\ cost\ per\ item\ in\ each\ period$

$h_t^i = inventory\ cost\ per\ item\ in\ each\ period$

$d_t^i = demand\ per\ item\ in\ each\ period$

$x_t^i = production\ lot\ size\ per\ item\ in\ each\ period$

$y_t^i = binary\ variable\ that\ indicates\ a\ positive\ production\ per\ item\ in\ each\ period$

$s_t^i = inventory\ of\ each\ item\ i\ at\ the\ end\ of\ period\ t$

$M_t^i = maximum\ production\ capacity\ per\ item\ in\ each\ period$

$L_t^k = available\ capacity\ per\ resource\ in\ each\ period$

$\alpha^{ik} = \ used\ capacity\ of\ the\ resource\ k\ with\ the\ production\ of\ each\ unit\ of\ item\ i$

$\beta^{ik} = \ setup\ time\ in\ resource\ k\ with\ the\ production\ of\ item\ i$

Objective function (1) consists in the minimization of the total production costs that include unit and fixed production costs and inventory costs. Then, constraint (2) expresses the satisfaction of the demand in each period, also being called the flow conservation equation. Equation (3) forces the setup variable to be 1 in the period t when there is production of a certain product, limiting this to a maximum limit. Finally, the generic restriction (4) imposes limits taking into account the available capacity of resources and the last equation (5) is related to the obligation of the variables to be non-negative or binary.
New constraints or changes to the existent ones were iteratively added to the model so that it would fit the characteristics of the production system in question.

2.2.1. Formulation

The following model was developed with the previously described Master Production Scheduling Model as a starting basis. The developed model uses the index t, with $1 \leq t \leq T$, to represent the discrete time periods, being T the final period at the end of the planning horizon. It also uses the index i that represent the products to be produced and two distinct indexes j and k to represent two different types of resources needed to produce the parts.

The objective is to plan the production over a determined planning period while minimizing costs (production, inventory and others) and satisfying the customer demand. The production costs are modelled through a fixed charge that is associated with the setup costs and a variable cost dependent of the lot size. This variable production cost is associated with an exponential parameter that allows to discourage production in the first periods, since the sooner the products are made the more inventory costs they incur. The inventory costs consist in a cost associated with each unit of product held at the end of each time period. There is a decision variable that represents the accumulated stock, s_{it}. Backlogging is allowed in the last considered period in the planning horizon, so it is possible to know the amount of product that was not produced due to lack of capacity, or other reason, represented by the variable b_i. This leads to the need of a backlog cost in the objective function so that the model tries to produce to the maximum of its capacity. The resource capacity is considered in each period since it is not infinite. The binary decision variable y_{jkt} allows to consider setup times since one is incurred when there is a change from one resource j to another and this is dependent of the allocation of resources, given by another binary variable w_{jkt}. Some variables are time dependent while also depending on the product and/or the resources, and others only depend on the product or resource it relates to. The formulation is as follows:

$$\min \sum_{i,j,k,t} ([p_i + e^{-t}]x_{it} + q_j y_{jkt} + h_i s_{it} + f_i b_i) \quad (6)$$

$$D_i - b_i = d_i \quad \forall i \quad (7)$$

$$s_{i,t-1} + x_{it} = d_i|_{t=|T|} + s_{it} \ \ \forall i,t \quad (8)$$

$$x_{it} = \sum_{j \epsilon J_i} z_{ijt} . \sigma_j \ \ \forall i,j,t \quad (9)$$

$$\sum_{i \epsilon I_j} z_{ijt} . \alpha_j = \sum_{k \epsilon K_j} L_{jkt} \ \ \forall j,t \quad (10)$$

$$\sum_{k \epsilon K_j} L_{jkt} + \sum_{k \epsilon K_j} \beta_{jk} . y_{jkt} \le C_{jt} \ \ \forall j,t \quad (11)$$

$$L_{jkt} \ge w_{jkt} \ \forall j,k,t \quad (12)$$

$$L_{jkt} \le C_{jt} w_{jkt} \ \forall j,k,t \quad (13)$$

$$\sum_{j \epsilon J_k} L_{jkt} + \sum_{j \epsilon J_k} \beta_{jk} . y_{jkt} \le N_{kt} \ \ \forall k,t \quad (14)$$

$$y_{jkt} \ge w_{jkt} - w_{jk,t-1} \quad \forall j,k,t \quad (15)$$

$$x \epsilon \mathbb{R}_+^{mT}, z \epsilon \mathbb{R}_+^{mnT}, s \epsilon \mathbb{R}_+^{m(T+1)}, b \epsilon \mathbb{R}_+^{m}, d \epsilon \mathbb{R}_+^{m}, L \epsilon \mathbb{R}_+^{nlT}, w \epsilon \{0,1\}^{nlT}, y \epsilon \{0,1\}^{nlT} \quad (16)$$

Indexes

$i = products, \quad 1 \leq i \leq m$

$j = resource, \quad 1 \leq j \leq n$

$k = machine, \quad 1 \leq k \leq l$

$t = time\ period, \quad 1 \leq t \leq T$

Decision variables

$$w_{jkt} = \begin{cases} 1, & if\ the\ resource\ j\ is\ allocated\ to\ the\ machine\ k\ in\ period\ t \\ 0, & otherwise \end{cases}$$

$$y_{jkt} = \begin{cases} 1, & if\ the\ machine\ k\ incurs\ a\ setup\ from\ j\ in\ period\ t \\ 0, & otherwise \end{cases}$$

$x_{it} = batch\ of\ product\ i\ to\ de\ produced\ in\ period\ t$

$z_{ijt} = number\ of\ cycle\ times\ of\ j\ that\ produce\ i\ in\ period\ t$

$s_{it} = inventory\ of\ product\ i\ at\ the\ end\ of\ period\ t$

$b_i = units\ of\ product\ i\ not\ produced\ during\ the\ considered\ planning\ horizon$

$L_{jkt} = load\ in\ resource\ j, in\ machine\ k\ and\ in\ period\ t$

$d_i = demand\ of\ product\ i\ to\ be\ produced$

Data

$p_i = unit\ production\ cost\ of\ product\ i$

$q_j = changeover\ cost\ to\ the\ resource\ j$

$h_i = inventory\ cost\ for\ item\ i$

$f_i = backlog\ cost\ for\ product\ i$

$si_i = initial\ stock\ for\ product\ i$

$\sigma_j = number\ of\ possible\ produced\ units\ with\ resource\ j\ (per\ cycle)$

$\alpha_j = \ cycle\ time\ of\ resource\ j$

$C_{jt} = available\ capacity\ of\ resource\ j\ in\ period\ t$

$\beta_{jk} = \ setup\ time\ of\ resource\ j\ in\ machine\ k$

$N_{kt} = available\ capacity\ of\ machine\ k\ in\ period\ t$

In this model the objective function (6) allows to minimize the sum of fixed productions costs, variable production costs related to setups, inventory costs and also the final backorder costs. In equation (7) it is given the possibility of backorder in the last considered period of the planning horizon since the variable d_i is only considered in this last period. Equation (8) allows to establish the lot sizes to be produced according to the final demand and available initial stock in each period. It forces the system to produce the needed units of product according to the demand and following a Just in Time policy, where it pushes the production until the last moment that it is possible while allowing to still respect the imposed due dates. This also allows to smooth the overall production and minimize the size differences of the batches. The equation (9) relates to the fact that each cycle time may produce a different number of parts depending on the resource j that it utilizes. It continues with the resource capacity related constraints in (11) limiting the resource j available capacity and in constraint (14) that limits the machines' available capacity considering, not only the producing time, but also, the setup times, be it the changeover times or the startup times. Before this, in equation (10) the load in the resources is stored in a variable and this then allows to put a limit in the productive capacity while equations (12) and (13) activate the resource allocation variable w. Constraint (15) considers the change from one mould to another in the same machine to define the binary variable y and allowing to incur a setup time and cost in the objective function, when needed. The final equation (16) allows to define the non-negative and binary variables.

2.3. Step 3: Implementation

The functionality and effectiveness of the model is tested using a commercial solver, CPLEX, that allows to model business issues mathematically and solve them with algorithms, producing precise and logical decisions. It presents a fully integrated development environment that supports the Optimization Programming Language (OPL).
CPLEX solves mixed integer programming (MIP) models with a branch-and-cut search. This procedure manages a search tree consisting of nodes in which every node represents an LP subproblem to be processed. This processing solves the subproblem while checking for integrality and analysing it further. Nodes are called active if they have not yet been processed and after a node has been processed, it is no longer active. CPLEX processes active nodes in the tree until either no more active nodes are available, or some limit has been reached (in IBM Knowledge Center).

A cut is a constraint added to the model that has the purpose of limiting the size of the solution domain for the continuous LP problems represented at the nodes, while preventing the elimination of legal integer solutions. The outcome is thus to reduce the number of branches required to solve the MIP (in IBM Knowledge Center).
Thus, the branch-and-cut approach involves running a branch-and-bound algorithm and applying cuts at the nodes of the tree.

Since the problem is considered to be of large size it is associated with significant computational complexity. This makes it difficult for standard solvers like CPLEX to address industrial-dimensioned problems in reasonable solution time (Dastidar and Nagi, 2005). One of the ways in which this is possible is to use the machine-mould compatibility in the injection moulding case (Nagarur et al. 1997). Each subproblem is then considered as a single-machine problem allowing to reduce the complexity of the general problem and is solved by heuristic procedures.

The implementation phase of optimization models in industrial companies is full of challenges, even considering the great progress that has recently been achieved in terms of the development of new mathematical formulations and conceptual frameworks. The difficulties encountered may be due to a wide range of problems. These relate to:

1. Understanding, on the part of the planners, the capacities and limitations of the model;
2. Definition of the specifications of the model and its impact on the decision-making process;
3. Definition of the most important trade-offs of modelling (model detail vs. computing time vs. quality of solutions);
4. Development of efficient models that are likely to be used for different functions within the company;
5. Evaluation of the models;
6. Progressive development of the models until they can be integrated as robust software applications.

These aspects demonstrate how the implementation of optimization methods has yet to go a long way until it turns into something trivial for the industry (Moniz et al., 2014).

3. CASE STUDY PRESENTATION

3.1. The Company

Yazaki's founding dates back to 1929 when Sadami Yazaki began selling electric wires for automobiles. After major changes in government regulations in 1935, Japanese companies were allowed to start domestic automotive production – with positive effects for Yazaki. In 1939 the company expanded its business and in 1941 the Yazaki Electric Wire Industrial Co. Ltd. was established with about 70 employees. At that time, the automotive engineering was a promising branch of the industry and so, in 1949, Sadami Yazaki made an important strategic decision: to focus on the production of automotive wiring harnesses. This was an innovative decision that resulted in today's global leadership. Since its beginning to this day, it has remained a company led by the different generations of the Yazaki family. Yazaki offers a diverse range of products in the global sectors of automotive and energy systems. Recently, they began expanding in a third sector, mainly in the areas of nursing care and environment-related business.

The manufacturing unit where this work was developed, Yazaki Saltano de Ovar (YSE), started its production in 1991 and, at this time, carries out the production of wiring harnesses, plastic injection components and energy distribution systems, among others. Since March 2019 they employ 2129 workers, of which 152 work in the mould department, where the plastic injection of components and subsequent assembly occurs. This department has a very significant production capacity, with 105 injection machines, 5 automatic assembly lines and other services. All this allows Yazaki to be one of the leading suppliers of renowned brands in the automotive industry.

3.2. The Current Production Planning Process

The company follows a Make-to-Stock production strategy (MTS) due to the complexity of the productive system and the high number of orders placed on a daily basis by many different clients, making it impossible to wait for fixed orders to begin production.

Production planning is based on forecasts that are sent by customers, and there is no defined or normalized value in terms of forecast time horizon or with how much advance it is necessary to present these forecast values. After the forecasts are obtained, the management system SAP, using the MRP optics, adjusts the quantities required to produce according to the values of the orders. This means, if there is already enough stock registered in the system then it does not have to produce more to satisfy the order, it only produces what is lacking to satisfy the real demand. Thus, the determination of the production lot sizes requires that an economic balance be found between the decrease of setup costs and the advantages of production smoothing.

Another method used by the company to ensure that it can satisfy the demand of customers is to define safety stocks or minimum stocks for the products, that is, after the products are dispatched they check if there is sufficient security stock. If it's not the case, the production order of the needed product is made. This method allows reducing the impact that a potential discrepancy between forecasts and real demand would have on production and fulfillment of delivery times. The safety stock value of each product depends on its classification in terms of sales (Table 3.1.) and production class (Table 3.2.). The product history in terms of maintenance and production is used to determine the classes.

Table 3.1. Sales classes of products

Sales class	
Class	Description
A	Greater demand
B	Intermediate
C	Lower demand

Table 3.2. Production classes of products

Production class	
Class	**Description**
A	More complications in production; Moulds requiring a lot of maintenance; Large number of breakdowns.
B	Intermediate
C	No production complications; Many moulds available.

The factors that most influence the production class are as follows:

- Inefficient mold;
- Color change;
- Product C.

By combining these factors, the SAP system will present the necessary amount of units needed to produce on that day or week, however, it only says the total quantities, not taking into account batch sequencing or the capacity or availability of the moulds and machines.

The product lead time is 4 weeks for most customers, with the exception of the one distribution center, for which the lead time is 1 week. A preparation time of 14 days is defined for all products (2 weeks considering that they work 7 days a week), that is, 14 days for the process of injection of components (1 week) and assembly process (1 week) combined, either in the company itself or in a subcontractor. This means that SAP will present, daily, weekly or monthly, what needs to be produced considering estimates of 14 days after the date considered. When the actual order is received, the system will check for sufficient units produced and, if not, add to the production needs of that day. The following chart (Figure 3.1) exemplifies this process:

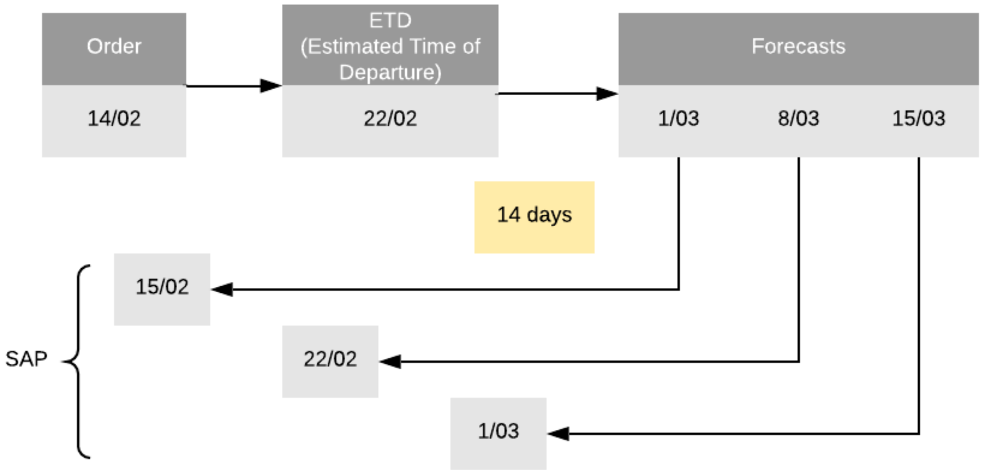

Figure 3.1 Example of forecast and order system

Each molded component has a defined number of units per box, so it is possible to know the details of what is produced. There is no deviation in terms of quantity of pieces per box (there are exceptions where the number of cavities available is not a divider of the number of pieces per box, in which case the box will have more parts , corresponding to the excess of the last injection – Example: Box with 5500 units and mold has 8 open cavities, 5500/8 = 687.5 injections, SAP rounds to 688 injections and the box will have a label with 5500 units but in reality will have 5504 units). The quality confirms if no parts are defective, those that are considered defective are declared scrap.

After having the information of quantities required to be produced, the operations are sequenced. Some aspects are considered:

1. There are certain machines that only work with specific molds;
2. It must be considered the tonnage of the machine (larger machines are able to use larger molds);
3. Some products have more than one mold that can be used;
4. The same mould can make several versions of the same product (when they have different colors the planner usually sequences from the lighter color to the darkest color, but this does not have any impact, it is only a convention);

5. The number of cavities available has to do with the fact that many times the parts used to alter the shape of the cavities are damaged and there is no stock for all units, only the most critical ones are kept in stock (most of the molds use this so it's an important factor), causing the corresponding cavities to close. In this way, the molds may not be used in their total capacity, that is, a mold can have 14 cavities, but only use 12, for example;
6. There are a few molds with all different cavities;
7. The number of open cavities and the number of units required is used to determine the number of injections required (injection = mold opens and closes, part falls by itself or is aided). The cycle time allows you to know how much time takes an injection.

The production version in SAP considers the subcontractor where the injected element goes and the machine that will produce it. This code is written in a successive way, example JS01/JS02/JS03, in which the letters correspond to the subcontractor (or to the company itself) that does the assembly of the components and the numbers do not correspond directly to a machine. The planners have another spreadsheet where you can see information about the processes that each machine performs, and the versions are associated with the corresponding machine.

Sometimes there are delays in production due to unavailability of raw materials, because of defects of the parts or because one of the molds suffered some kind of damage. If there is no other mould available that allows making the desired component, it becomes dependent on the maintenance work that is often time-consuming. When this happens, production control is in charge of realizing the impact of this delay. There may be no impact due to the fact that sufficient units have already been produced (caused by discrepancies between forecasts and actual values), the delay being covered by the safety stocks, or even because the customer/subcontractor/ distribution center is also lagging behind.

When it is necessary, because of lack of capacity, moulds are provided to subcontracted companies, if possible, and orders are made so that they perform the process of injecting the components that are needed. Sometimes it may happen some unforeseen issue in the subcontracted company and it will not be able to meet the delivery dates set. In this case, an impact assessment is made. There is the possibility of not having any impact, or it may still be possible to coordinate this extra production in Yazaki because sometimes there are extra molds that can be used. If it is not possible to move the production to an external company, it is up to the decision-maker to start a negotiation process with the client. In Annex A is presented a chart with the followed planning methodology.

3.3. Problem Description

The company uses a centralized management system that allows them to manage all processes, including production planning. However, this system has limitations when it comes to planning considering the capacity of the injection machines and the determination of the size of the productive batches of injected components. This implies an increase in the work load of the planners that need to evaluate the best production sequence, the best batch size, and subsequent manual insertion in the system. This demonstrates the lack of a method based on mathematical models and that use the data from the injection machines and production to predict the optimal size of the batches and their planning considering the variables of the process, which would allow an increase in efficiency of the molding process and resource usage.

Thus, our problem is motivated by a production planning and lot-sizing problem faced by a plastic injection manufacturing plant that produces components for the automotive industry. The facility has 5 production lines, with a total of 105 injection molding work centers and 508 molds that are able to produce approximately 879 products. These parts are considered finished products in the designed model, even though, in the real production system, they proceed further into an assembling process that turns them into the finished product that is going to be delivered to the client. The production runs through three 8-hour shifts, 7 days a week and every injection machine produce the same component for at least 2 hours in a row before a changeover to another product. However, this has a lot of variability because there are machines that produce the same part for a long time, depending on the demand requirements. This introduces a variability source in the production system that increases the complexity of the model. The system follows other production rules, such as the ones described in the previous section and there are a number of constraints that affect the production. One of the most important consists in the compatibility between the molds, the injection machines and the parts that are to be produced by these resources. Since a product can only be made by a specific set of molds and, in a parallel way, a mold can only be used in a certain set of machines, the compatibility is restricted, causing the model to have a lot of unavoidable constraints.

4. RESULTS AND DISCUSSION

After doing the ACB-XYZ analysis of the finished products and correspondent semi-finished products (since the data necessary to do this analysis is related to the finished product but the model uses information about the semi-finished product) it was possible to compile in . the correspondent class to the products in the used data set.

Table 4.1. ABC-XYZ analysis

Class	A	B	C
X	43 produtos	71 produtos	38 produtos
Y	1 produto	17 produtos	36 produtos
Z	0	0	2 produtos

According to the collected data it is possible to observe that the molding department of the company produces a great variety of components in a single period of planning. This increases the complexity of the system itself, as well as the need to optimize the resource capacity and mold changeover rates.

The problem instances were generated using data provided by the injection molding company. The data considered 208 products that were to be produced in the time period of a week, with correspondence to 239 moulds and 105 available injection machines. These machines are of different sizes or tonnage, meaning that they can only work with a limited set of moulds, but also, each product can also be produced by a limited set of moulds. This limited compatibility between resources and products is one of the characteristics that the envisioned model aims to simulate. In order to better analyse the model's possible applicability, several runs were made with different data sets and its results compared.

The try-outs had the following characteristics:

1. Only “A” products;
2. “A” products + “B” products;
3. Full data set of products (“A” +” B” +”C”);

With the final formulation of the lot-sizing model it was possible to solve the three different-sized problems within acceptable computational time. The results are as follows:

Table 4.2. Data set specifics with only "A" products

Products	44
Moulds	77
Machines	87

Table 4.3. Computational results from "A" products problem

Constraints	54518
Binary variables	3514
Continuous variables	3035
Gap	1,15%
Computation time	8.36 seconds

With a total demand of 13 881 508 units of "A" products, the solution has 1 366 498 units in backorder, which means it has approximately 9.8% of backorder. The average machine occupation rate is of 66% and the average mold occupation rate is 60%. This production requires 123 setups to be carried on the considered machines.

Table 4.4. Data set specifics with "A" and "B" products

Products	132
Moulds	179
Machines	104

Table 4.5. Computational results from “A” and “B” products problem

Constraints	148511
Binary variables	7910
Continuous variables	7460
Gap	2,78%
Comp time	1.01 minutes

With a total demand of 23 306 206 units of “A” and “B” products, the solution has 2 125 099 units in backorder, which means it has approximately 9.1% of backorder. The average machine occupation rate is of 88% and the average mold occupation rate is 41%. This production requires 217 setups to be carried on the considered machines.

Table 4.6. Full data set specifics

Products	208
Moulds	239
Machines	105

Table 4.7. Full problem computational results

Constraints	200268
Binary variables	10150
Continuous variables	10349
Gap	2,92%
Comp time	1.56 minutes

With a total demand of 25 406 894 units, the solution has 2 568 078 units in backorder, which means it has approximately 10.1% of backorder. The average machine occupation rate is of 94% and the average mold occupation rate is 34%. This production requires 251 setups to be carried on the considered machines.

Comparing the three try-out runs with different data sets we are able to conclude that all three are able to compute a solution in under 2 minutes with an integrality error of less than 3%. The backorder percentage remains approximately the same in all the try-outs, between 9% - 10%. With the increase in the number of products along the different data sets the occupation rate of the machines also suffers a very substantial increase but, on the other hand, the mold occupation rate decreases. As would be expected, the number of needed setups also increases.

The occupation rates distribution by machines (Figure 4.1) and molds (Figure 4.2) is the following:

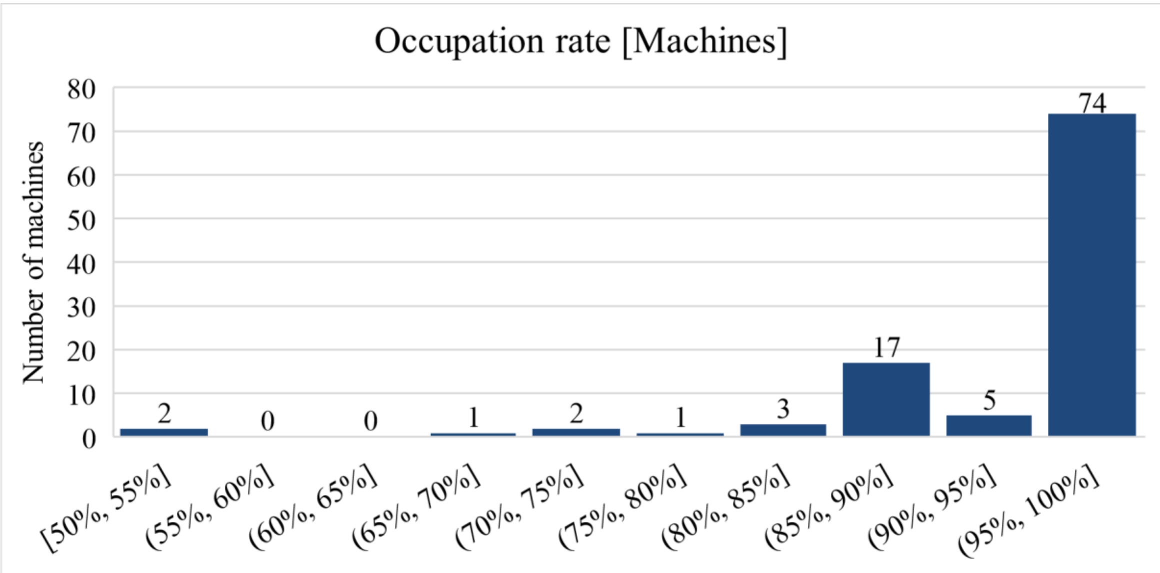

Figure 4.1. Machine's occupation rate distribution

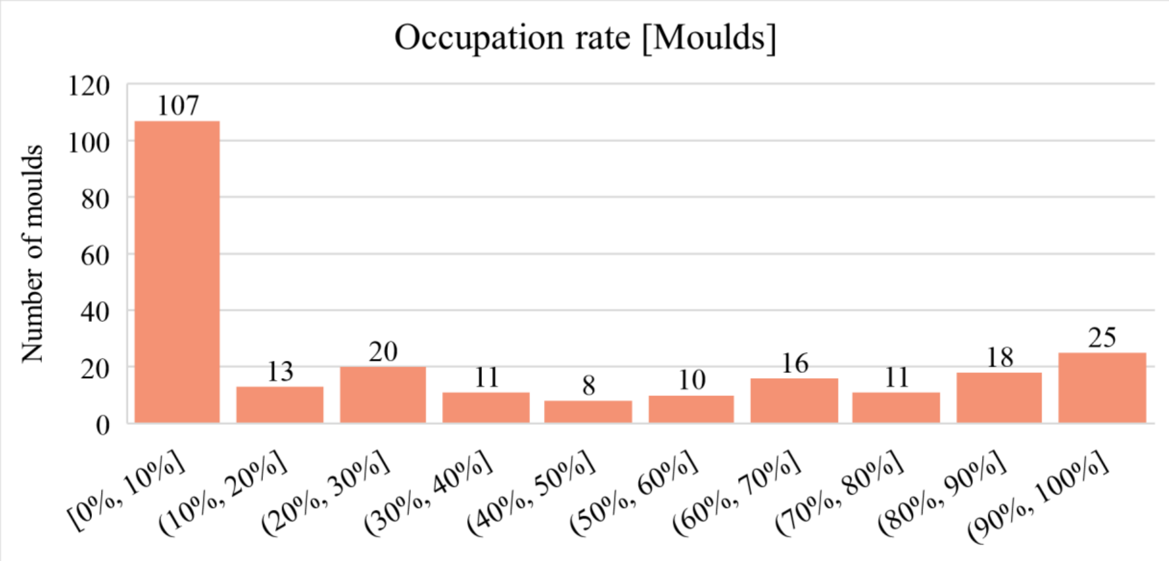

Figure 4.2 Mold's occupation rate distribution

From the occupations rates charts it is possible to observe that most of the solution backorder is probably due to lack of the machines' productive capacity since 74 out of 105 machines are in the 95%-100% occupation range. Whereas the machines lack capacity, the mold paradigm is almost opposite. Most of the molds are in the 0%-10% occupation range, meaning that there are many molds that are needed, given the large variety of products that are offered, but these are not being used to their full capacity, either due to the lack of machine availability or due to low demands of the correspondent products.

The solved problem cost distribution is presented in Figura 4.3 where it features all the considered costs in the objective function.

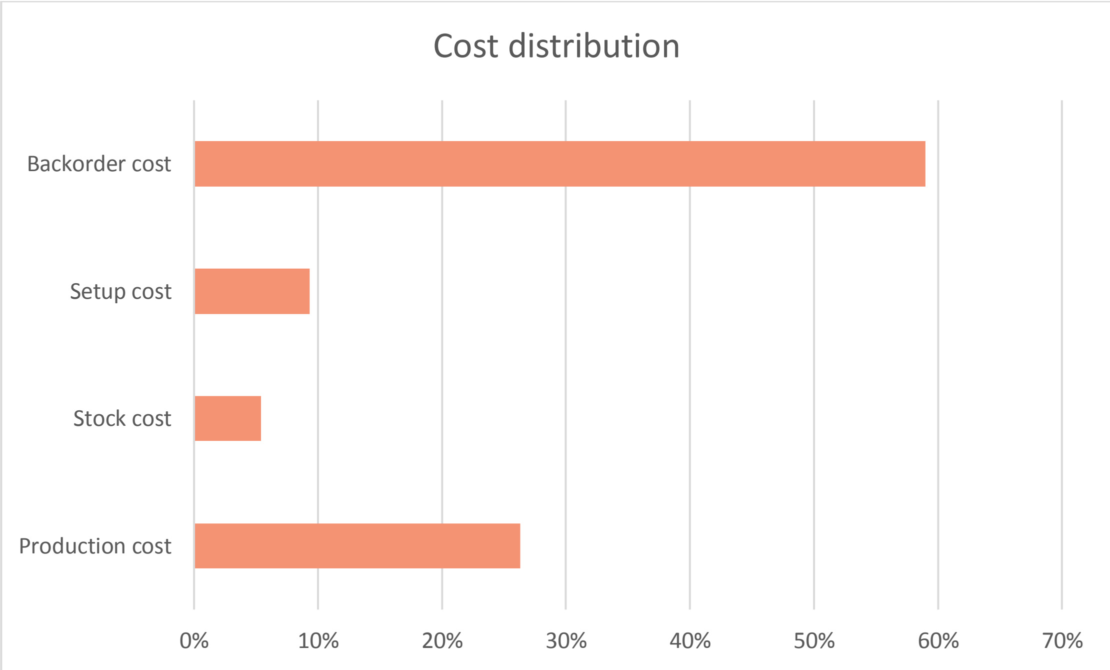

Figura 4.3. Cost Distribution

The backorder cost is significantly higher than the rest of the cost making almost 60% of the total cost. This is a result of limitations in the lot-sizing model. Since the company doesn't always have capacity to satisfy all the weekly demand it was necessary to add the backorder option at the end of the planning period. This also implied complementing the model with a backorder-related cost. This cost was adjusted in a way that the model would always try to produce to the maximum of its capacity. However, that leads to a substantial increase in the backorder cost, since there are still products that need to be produced in the subsequent week.

A way to avoid this would be to do an aggregate capacity analysis where it would be calculated the maximum possible production, and the difference between that value and the concrete demand would be passed to the following week.

In Figure 4.4 it is possible to see that most machines only need one, two or three setups during the week and the maximum number of setups is six, this only being true in one of the injection machines

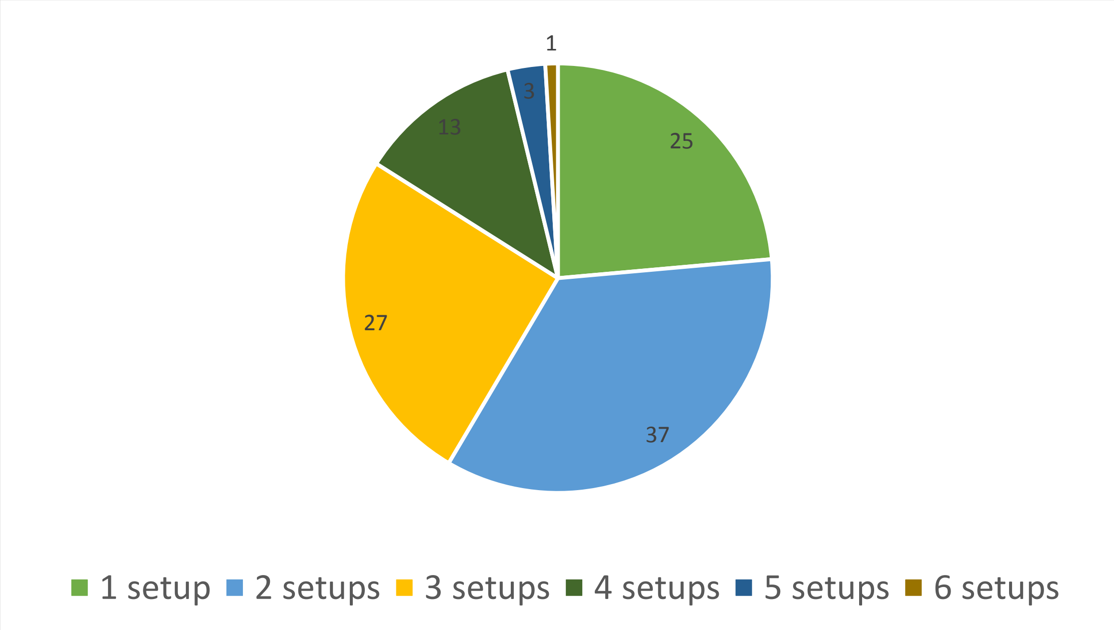

Figure 4.4. Machines by number of incurred setups in a full planning horizon

It's important to reiterate that the created model is just a complement to the planner's work, as there remain too many variables in the productive system for it to be able to rely solely on a mathematical and programming model. The human factor is important in dealing with unpredictable events that a model like this wouldn't be able to predict.

After analysing the results there were several characteristics that were deemed important to add to the model in order to make it more suitable to the production and planning process in question:

- The components being produced are mostly made of two main parts – a connector and a front holder. When planning production, the planner tries to do it in a way that they can be sent to assembly at the same time. Therefore, a penalty should be added to the model that privileged the production of those corresponding parts at the same time;
- Since the parts are considered semi-finished and they further go into an assembly process, the model could be further enhanced so that it synchronized production with the assembling flow;

- In the current model, raw material changeovers are not considered. Since these increase the setup time significantly it would be necessary to add a material variable related to each product and the model would try to minimize this type of setups;

These would allow further research of the applicability of the model in the practical industrial environment in question.

5. CONCLUSION

In modern manufacturing companies, flexibility and innovation is crucial, because it allows them to deal with market changes and growing competitiveness. A manufacturing firm's ability to compete in the market may rely in making the right decisions in lot sizing, since it will affect directly the system performance and its productivity. Therefore, developing and improving solution procedures for lot sizing problems is very important. When developing lot-sizing models is important to relate them with cases observed in practice since this provides sound industrial validations for the research on extended lot-sizing models. The applications of deterministic lot-sizing can be found in many different industries such as injection moulding.

This work's primary objective was to create a lot-sizing model that could be used in the production planning process of an industrial plant. This model was formulated always with the production system specific characteristics in mind, such as parallel machines, setup carry-over and backorders. Although it was developed with a certain company in mind, it is simple enough to be applied to other instances, which is always an advantage in this type of mathematical models.

The implementation in a commercial solver allowed to test different data instances with variable characteristics and the obtained results were deemed valuable in a way that it can be used as a starting-point in the planner's work. On the other hand, we also arrived at the conclusion that the model would need further development in some areas for it to be implemented in the production planning process.

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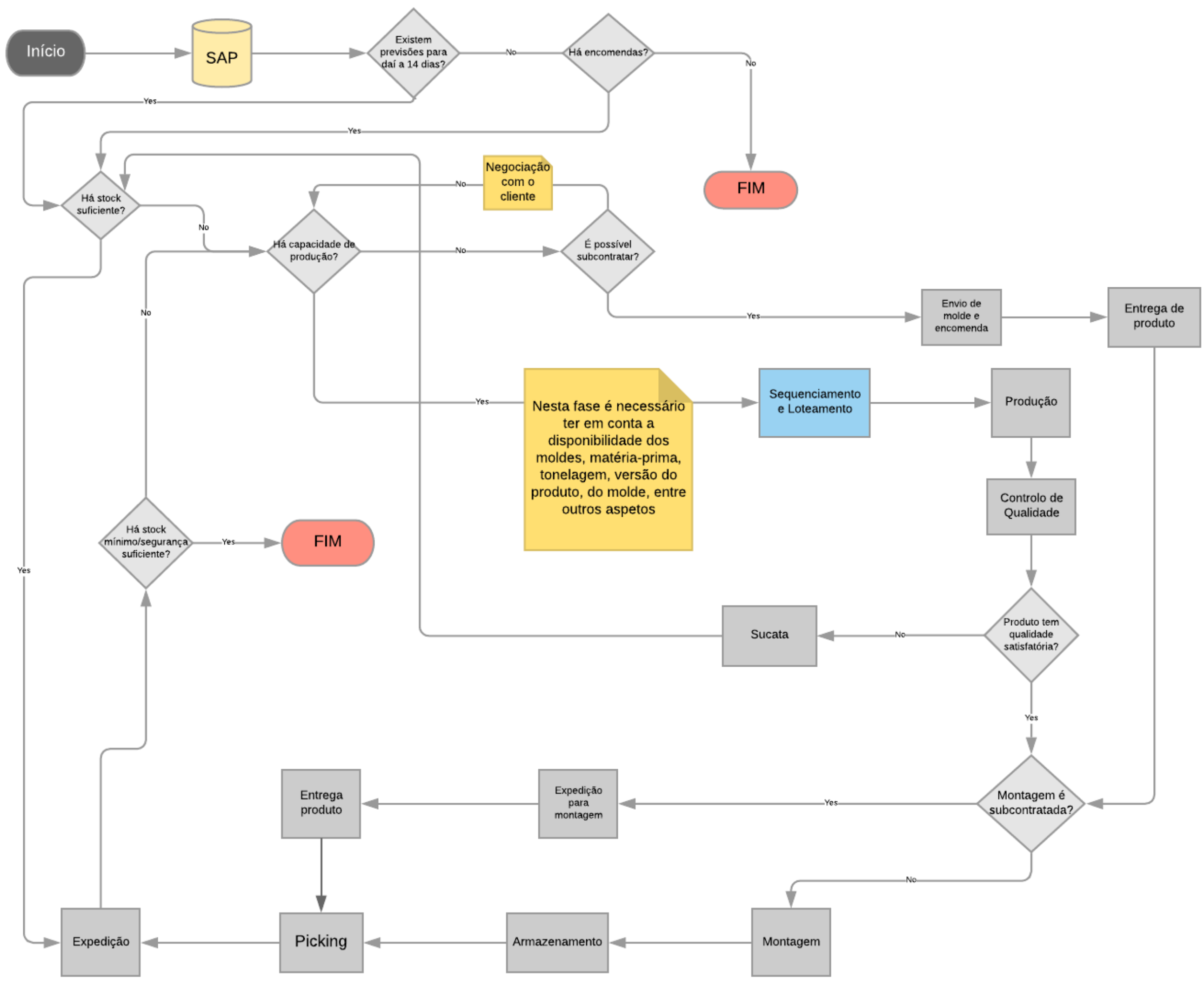
ANNEX A


Início
SAP
Existem previsões para daí a 14 dias?
No
Há encomendas?
No
Yes
Yes
FIM
Negociação com o cliente
No
Há stock suficiente?
No
Há capacidade de produção?
No
É possível subcontratar?
Yes
Envio de molde e encomenda
Entrega de produto
No
Yes
Nesta fase é necessário ter em conta a disponibilidade dos moldes, matéria-prima, tonelagem, versão do produto, do molde, entre outros aspetos
Sequenciamento e Loteamento
Produção
Controlo de Qualidade
Há stock mínimo/segurança suficiente?
Yes
FIM
Yes
Sucata
No
Produto tem qualidade satisfatória?
Yes
Entrega produto
Expedição para montagem
Yes
Montagem é subcontratada?
No
Expedição
Picking
Armazenamento
Montagem