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Escola de Engenharia

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# Serial Batch Processing Machine Scheduling - A Cement Industry Case Study

Dissertação de Mestrado
Mestrado em Engenharia de Sistemas

Trabalho realizado sob a orientação do
**Professor Doutor José António Oliveira**
e do
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outubro 2018

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Ano de conclusão: 2018

Mestrado em Engenharia de Sistemas



Universidade do Minho, ____/____/_______

Assinatura: ____________________________________________________

To my godparents, whom I

miss so much.

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# Acknowledgments

I could not let this moment of my life pass by without saying thanks to the ones who made all this work and my academic life possible. Over the past five years of my academic experience I was able to exceed my expectations and build memories with people I will never forget.

First of all, I would like to thank my advisors José António Oliveira, Ph.D and Luís Dias Ph.D, for all the encouragement and support in this process of becoming a Master.

To my parents, because without their effort I could never become what I am now. Thank you for the education you gave me, the life values you passed me and, most of all, thank you for always giving me the freedom to choose whomever I wanted to be.

To my youngest brothers, Carlos, Marco e Afonso, for teaching me that sometimes human relationships are not easy to deal with and having patience, listen and understanding the point of view of the other person is the most important thing if we want to become better versions of ourselves.

To my grandpas for being an example of strength and for proving to me that even if life is not easy, it is always worth living. To the ones who have already left, my godparents, I am just so grateful for having so much of you in me that I could not ask for more, I hope you are proud of me.

To my boyfriend, Pedro, for being my confidant, the one whom I share everything with, and the one who is always there for me whenever I need. Thank you for always having a friendly word to say and for always cheer up my day.

To my project colleagues and friends, João Fonseca and Ricardo Alves, for all the help they gave me when I needed, for all the good conversations and for always encouraging me to be a better person and professional. It was a pleasure working with you.

To my family, in general, especially to my cousins Salomé, Luís and António, for all the memories and companionship over the years. To my childhood friends, to my biomedical graduation friends and to my master's degree friends, thank you for all the adventures, sense of friendship, funny moments and all the support over the years.

To all the teachers who crossed my school path, thank you for all the lessons.

Last, but not least, to God, for putting all these people in my life and for all the gifts He presented me with.

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# Abstract

This work arises in the Cement Industry in the process of scheduling the clients to the warehouse and assignment to docking bays. The goal is to solve the scheduling and assignment problem, to improve both company's service levels and the efficiency of its resources. After the real problem analysis, it was possible to conclude that it could be solved as a batching machine scheduling problem, where the jobs are the clients to be schedule, and the machine is the warehouse. The problem can be described as $1 \mid r_j, s-batch \mid C_{\max}$. A Mixed Integer Linear Programming (MILP) model was proposed. However, as the number of jobs increased it started having computational difficulties. To overcome the problems of the MILP model two heuristics were proposed. The first one is a Constructive Algorithm (CA) that creates a first solution for the problem. The second heuristic is a metaheuristic algorithm, based on Simulated Annealing procedures, that starts with the initial solution of the CA and through three possible moves starts constructing the neighboring solutions space. After constructing the neighboring solutions space, it returns the best solution found. The computational tests proved that both the MILP model and the heuristics can ensure both feasible and optimum solutions. However, the MILP model consumes more computational resources. For some larger instances and giving a maximum limit of computational time of 8 hours, the MILP model cannot reach the optimality, nor the good results obtained by the heuristics, for those larger instances.

The machine scheduling is a good approach for scheduling the trucks to the warehouse. Since it is also an innovative approach for the problem, considering the literature studied, maybe this work will inspire others to work on this idea or, at least, serve as a basis for future researches.


**Key-words:** scheduling, batch processing machine, cement industry, MILP, heuristic methods.

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# Resumo

Este trabalho tem como cenário a Indústria Cimenteira no processo de agendamento de clientes para atendimento no armazém e atribuição de pontos de carga. O objetivo é resolver o problema de agendamento visando otimizar tanto os níveis de serviço da empresa bem como a eficiência dos seus recursos. Depois da análise detalhada do problema real foi possível concluir que este podia ser resolvido como um problema de processamento em lotes em máquina única, onde as tarefas a agendar seriam os clientes e a máquina o armazém. O problema pode então ser descrito como $1 \mid r_j, s-batch \mid C_{\max}$. Um modelo de Programação Linear Inteira Mista (PLIM) foi proposto. Contudo, à medida que o número de tarefas aumentava, o modelo começava a ter dificuldades computacionais na obtenção de solução ótima. Para ultrapassar essas dificuldades, foram desenhadas e propostas duas heurísticas. A primeira é um Algoritmo Construtivo (AC) capaz de retornar uma solução inicial. A segunda, uma meta-heurística, baseada na abordagem do *Simulated Annealing*, que trabalha a solução inicial gerada pelo AC, através de três movimentos possíveis, e gera uma vizinhança de soluções. Depois, procura e retorna a melhor solução possível dessa vizinhança. Os testes computacionais provaram que tanto o modelo de PLIM como as heurísticas são capazes de retornar tanto soluções possíveis como ótimas. Contudo, o modelo de PLIM consome muitos mais recursos computacionais do que as heurísticas. Para instâncias de tamanho superior, dado um tempo de computação máximo de 8 horas, o PLIM, não conseguindo atingir a solução ótima, nem sequer consegue atingir soluções tão boas como as das heurísticas.

A abordagem de agendamento em máquinas, utilizada neste trabalho, mostrou-se ser uma boa abordagem para o agendamento de clientes no armazém. Para além disso, esta é uma abordagem inovadora, tendo em conta a literatura estudada, e, talvez possa inspirar outros autores a trabalhar nesta ideia ou então servir de base para pesquisas futuras.

**Palavras-chave:** agendamento, máquina de processamento em lotes, Indústria Cimenteira, PLIM, métodos heurísticos.

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# List of Acronyms

| | |
|---|---|
| **AMPL** | A Mathematical Programming Language |
| **CA** | Constructive Algorithm |
| **CI** | Cement Industry |
| **CPS** | Cyber-Physical Systems |
| **ERD** | Earliest Release Date |
| **IoS** | Internet of Services |
| **IoT** | Internet of Things |
| **LS** | Local Search |
| **MILP** | Mixed Integer Linear Programming |
| **SA** | Simulated Annealing |
| **SCM** | Supply Chain Management |
| **UH4SP** | Unified Hub for Smart Plants |

# 1. Introduction

In this technological and competitive era that companies currently live in, being alert and aware of its own weaknesses, can be decisive for future success. Having the processes synchronized and available for optimization at any time, can help companies improve and gain competitive advantages. In fact, companies that recognized what processes need optimizations or updates, are more prepared for any changes that the future holds. Part of these processes include the logistics activities. The logistic field makes part of almost every industry or activity, and it is responsible for the flow of goods and information. Having the logistics operations optimized is, in many cases, half of the way for companies to succeed.

In this first chapter a brief framework of this study is going to be presented as well as the main objectives. Last, the main structure of the work will be presented.

## 1.1. Study Framework

This work arises in a project called Unified Hub for Smart Plants (UH4SP). The goal of the project UH4SP is the development of a software service-oriented architecture and technology solutions, under the paradigm of Internet of Things (IoT) and Industry 4.0. This revolution called Industry 4.0 or Smart Manufacturing or Industrial Internet, apparently, has the potential to affect entire industries by transforming the way how goods are designed, manufactured, delivered and payed (Hofmann & Rüsch, 2017). Trends and new catchwords such as digitalization, the IoT, Internet of Services (IoS) and Cyber-Physical Systems (CPS) are becoming more and more relevant nowadays due to this 4$^{th}$ revolution (Ford, 2015; Hofmann & Rüsch, 2017). Basically, these concepts value the Internet connection to allow the total interaction and exchange of information not only between humans and human and machine but also between the machines themselves (Roblek, Meško, & Krapež, 2016). This is what the UH4SP intends, through the Internet connectivity, to promote a corporate and aggregate vision of industrial units' operations dispersed across different geographies through remote and local access. The first industrial units in study, called the pilot industry, are cement units. However, this project is not restricted to cement industries, in fact, the goal is to expand the horizons and create a software able to suit any type of industry.

Among the objectives of the UH4SP project is the optimization of operations in industrial units through the development of heuristics to optimize logistics processes. This objective is mostly what defines the objectives of this work. The analysis of the logistics processes and identification and resolution of problems was the big motivation of this dissertation since the major goal is having an optimized and integrated supply chain capable of ensuring the success of companies. Plus, to ensure the correct product, in the right time, exact quantity, in the programmed destination, by the authorized person, in right conditions and at the best price are challenges that require a high level of organization of the logistics processes. In this context, the systems of control, monitoring, optimization and automation of the logistical flows that involve loading and unloading operations in industrial units have assumed a special preponderance. These loading and unloading operations are the main logistics operations in study in this work, which makes them the target of study.

## 1.2. Objectives

Since the UH4SP has a component responsible for optimizing the logistic process of loading and unloading the goods, in cement units, this is, in fact, the logistic operation that will be analyzed. In other words, the main goal of this work is to study the operations of loading goods, in cement warehouses. This study includes the analysis of all the problem characteristics and the proposal of solutions to improve the company's service levels and resources' efficiency. These solutions come in form of both exact method and heuristics models. In the end, the objective is to understand if the proposed algorithms are good approaches for the problem and to understand the importance of this type of studies in the innovation field.

Besides, this work also aims to be a contribution or motivation for other people who are trying to solve similar problems since, considering the actual literature, it was not possible to find many studies about this matter. However, the fact that there is not many contributions in the literature about this topic does not mean it is a theme of little importance, on the contrary. The loading operations are daily operations in a big majority of industries and that is why it is such an important and relevant study.

## 1.3. Document Structure

In the second chapter of this work – the Literature Review – a detailed literature review of the problem in study will be presented. Themes such as the logistics and supply chain, distribution process and warehousing operations will be explained. Plus, the scheduling field will also be addressed.

In the third chapter – the Problem Description – a detailed description of the problem will be presented as well as the proposed problem formulations. These proposed formulations of the problem are the single machine scheduling, the batch processing machine and the parallel machine scheduling.

In the fourth chapter – the Methodology – the final assumptions made to start modeling the problem are presented, as well as the mathematical formulation. In this chapter the batch processing problem will be addressed since this is the analogy used to solve the loading operations in the warehouse. Plus, it is in this chapter where the Mixed Integer Linear Programming (MILP) model is addressed as well as the heuristic methods – both the Constructive Algorithm (CA) and the metaheuristic method.

In the fifth chapter – the Computational Experiments – the instances generated to test the algorithms will be presented as well as the obtained results.

The sixth and last main chapter – the Conclusion – will include the main conclusions of the work as well as future work proposals.

## 1.4. List of Publications

The third chapter of this dissertation presents the description of the case study problem. The case study was the basis for the development of six scientific research publications, published or submitted to publication. The full list of publications is presented below.

(1) Fonseca, J., Alves, R., **Macedo, A. R.**, Oliveira, J. A., Pereira, G. and Carvalho, M. S. (2019), Integer programming model for ship loading management, in J. Machado, F. Soares and G. Veiga, eds, Innovation, Engineering and Entrepreneurship, Springer International Publishing, Cham, pp. 743-749.

(2) **Macedo, A. R.**, Fonseca, J., Alves, R., Oliveira, J. A., Carvalho, M. S., Pereira, G. (2018). The impact of Industry 4.0 to the environment in the cement industry supply chain. Proceedings of ECOS 2018 - The 31st International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS). Presented at the ECOS 2018 Conference.

(3) Alves, R., Fonseca, J., **Macedo, A. R.**, Veloso, H., Dias, L., Pereira, G., Carvalho, M. S., Figueiredo, M., Oliveira, J. A., Martins, C. and Abreu, R. (2018), Cement Industry - A Routing Problem, Cement Update by Daily Cement (5), 10-15.

(4) Fonseca, J., **Macedo, A. R.**, Alves, R., Veloso, H., Dias, L., Carvalho, M. S., Pereira, G., Figueiredo, M., Oliveira, J. A., Abreu, R. and Martins, C. (2018), Rules for Dispatch, BMHR 2018 supplement in World Cement (September).

(5) **Macedo, A. R.**, Alves, R., Fonseca, J., Veloso, H., Dias, L., Figueiredo, M., Pereira, G., Carvalho, M. S., Abreu, R. and Martins, C. (n.d.), What can we learn from Industry 4.0: Opportunities in the logistics field on Cement Industry.

(6) Veloso, H., Vieira, A., Alves, R., Fonseca, J., **Macedo, A. R.**, Pereira, G., Dias, L., Carvalho, S., Figueiredo, M. (2018), Simulation in cement industry, CemWeek (July).

# 2. Literature Review

## 2.1. Logistics and Supply Chain Management

Logistics and Supply Chain Management (SCM) have been an issue of study and curiosity for many researchers. In fact, there is a lot of research concerning this study field, starting with the definition, the impact and ending with the evolution of these two topics.

However, logistics and SCM are not new ideas considering that their practice is guided by some basic concepts that have not changed much over the centuries (Hugos, 2018). From the building of the pyramids to the relief of hunger in Africa, the principles underpinning the effective flow of materials and information to meet costumers' requirements have altered little (Christopher, 2016). Nevertheless, it is only in the latest decades (Mangan & Lalwani, 2016) that logistics and SCM finally became recognized as a key part to achieve the overall business success (Rushton, Croucher, & Baker, 2010). With this recognition, the appreciation of the scope and importance of logistics and the supply chain has led to a more scientific approach being adopted towards this subject (Gundlach, Bolumole, Eltantawy, & Frankel, 2006; Rushton et al., 2010). This approach has been focusing at the overall concept of the logistics function and at the individual sub-systems. Much of this approach has addressed the need for, and means of, planning logistics and the supply chain, but has also considered some of the major operational issues (Rushton et al., 2010).

Furthermore, not only are logistics and SCM key features of today's business world, but they are also important for the public sectors. Much of the logistics thinking and practice are in a manufacturing context, more specifically in the textile industry (Lummus & Vokurka, 1999). However, with the increasingly and successful application of logistics and SCM principles in a services context proves the importance and relevance of this topic of study. For instance, the banking and hospitals are good examples of service based activities that took advantage of the proficiencies of logistics and SCM, where the emphasis has shifted to serving more customers, better, faster and cheaper (Mangan & Lalwani, 2016).

### 2.1.1. Clarification of the Concepts

Even though there is no 'true' definition that should be meticulously applied, because products differ, companies differ, and systems differ (Rushton et al., 2010), the underlying concept of logistics can be defined as:

"*Logistics is the process of strategically managing the procurement, movement and storage of materials, parts and finished inventory (and the related information flows) through the organization and its marketing channels in such a way that current and future profitability are maximized through the cost-effective fulfilment of orders* (Christopher, 2016)."

In sum, logistics is a diverse and dynamic function that must be flexible and has to change according to the various constraints and demands and with respect to the environment in which it works (Rushton et al., 2010). That said, logistics is essentially a planning orientation and framework that seeks to create a single plan for the flow of products and information through a business. SCM, on the other hand, builds upon this framework and seeks to achieve linkage and collaboration between the processes of other entities in the pipeline, i.e. suppliers and customers, and the organization itself (Christopher, 2011; Mentzer, Esper, Stank, & Esper, 2008). In other words, logistics typically refers to activities that occur within the boundaries of a single organization while supply chains refer to networks of companies that work together and coordinate their actions to deliver a product to market (Hugos, 2018).

The focus of SCM is on the cooperation and trust and the recognition that, accurately managed, the 'whole can be greater than the sum of its parts' (Christopher, 2011; Mangan & Lalwani, 2016). A definition of SCM proposed by Christopher (2016) is:

"*The management of upstream and downstream relationships with suppliers and customers in order to deliver superior customer value at less cost to the supply chain as a whole*."

In this context, there are some authors that defend that the phrase 'supply chain management' should really be termed 'demand chain management'. Their idea is that the definition should reflect the fact that the chain should be driven by the market, not by suppliers (Christopher, 2011). Equally the word 'chain' should be replaced by 'network' since there will normally be multiple suppliers and, indeed, suppliers to suppliers as well as multiple customers and customers' customers to be included in the total system (Christopher, 2011; Mangan & Lalwani, 2016). So, extending this idea, it has been suggested that a supply chain could more correctly be defined as:

"*A network of connected and interdependent organizations mutually and cooperatively working together to control, manage and improve the flow of materials and information from suppliers to end users* (Aitken, 1998)."

At this point, it is possible to recognize that the concept of SCM, even if relatively new, is in fact no more than an extension of the logic of logistics. While logistics management is primarily concerned with optimizing flows within the organization, SCM, instead, recognizes that internal integration by itself is not enough (Christopher, 2011). Also, traditional logistics focuses its attention on activities such as procurement, distribution, maintenance, and inventory management, while SCM acknowledges all traditional logistics and includes activities such as marketing, new product development, finance, and customer service (Hugos, 2018).

### 2.1.2. Competitive Advantages through the Supply Chain

With the concepts of logistics and SCM addressed and explained it is now understandable why throughout the history of mankind wars have been won and lost through logistics strengths and capabilities – or the lack of them (Christopher, 2016). Also, while previously considered a function with little added value, and primarily focused on cost management, logistics has evolved into a source of competitive advantage (Christopher, 2016; Mentzer et al., 2008; Rushton et al., 2010). But, what are these competitive advantages and how can companies achieve them. Firstly, the source of competitive advantage is found in the ability of the organization to differentiate itself from its competition, in a way that adds value for the costumer (Christopher, 2016; Fawcett, Birou, & Cofield Taylor, 1993). Secondly, they can be found in the capacity of the companies to operate at lower costs and hence at greater profits. Competitive advantages are so important that have become the concern of every manager who is alert to the realities of the marketplace, and who is seeking for a sustainable and defensible company's growth (Christopher, 2011; Stadtler, 2015). An increasingly powerful way to achieve cost advantages comes not necessarily through volume and the economies of scale but instead through logistics and SCM (Christopher, 2011). It is in this idea that this work will be grounded on. The idea that with logistics optimizations it is possible to improve profits and gain competitive advantage (Christopher, 2016).

Logistics costs have become, then, a main target to be eliminated for most companies, nowadays. These costs can appear, for instances, in the plants, depots and warehouses that form the logistics network (Christopher, 2016). Plus, the materials handling equipment, vehicles and other equipment involved in storage and transport can also add considerably value to the total sum of fixed assets (Christopher, 2016). In the past, this total sum of fixed assets associated to logistics costs had gone unmeasured since they were essential to the business worldwide (Fawcett et al., 1993).

One approach to reducing global logistics costs while increasing service levels has been to trust on third-party suppliers of transport and logistics services (Christopher, 2016; Fawcett et al., 1993). Therefore, many companies have outsourced the physical distribution of their products partly to move assets off their balance sheet (Fawcett et al., 1993). Warehouses, for example, with their associated storage and handling equipment represent a sizeable investment (Christopher, 2011). But, in some cases it is not possible for companies to outsource so they must improve by themselves to reduce costs.

To conclude the ideas presented so far, it is possible to witness that in several industries, logistics costs represent a big proportion of total costs and, it is possible to make major cost reductions through essentially reengineering logistics processes (Christopher, 2011; Fawcett et al., 1993). Additionally, and supporting what initially has been mentioned about logistics and competitive advantage, following these ideas, logistics management has the potential to assist the organization in the achievement of cost advantages (Christopher, 2016; Lummus & Vokurka, 1999).

To better understand where there can be cost improvements and competitive advantages through the supply chain it is necessary to distinguish all the different stages that constitute any of them. Even though these stages are different, they are not independent from each other. So, it is necessary to emphasize that the primary philosophy behind the logistics concept is the planning and coordination of materials flow from source to user as an integrated system (Lummus & Vokurka, 1999). Rather than, as was so often the case in the past, managing the goods flow as a series of independent activities (Christopher, 2016). Thus, under this integrated approach the goal is to link the marketplace, the distribution network, the manufacturing process and the procurement activity in such a way that customers are serviced at higher service levels and yet at lower cost, gaining competitive advantages (Christopher, 2011; Stadtler, 2015). The Figure 1 illustrates the different stages that form almost every supply chain.

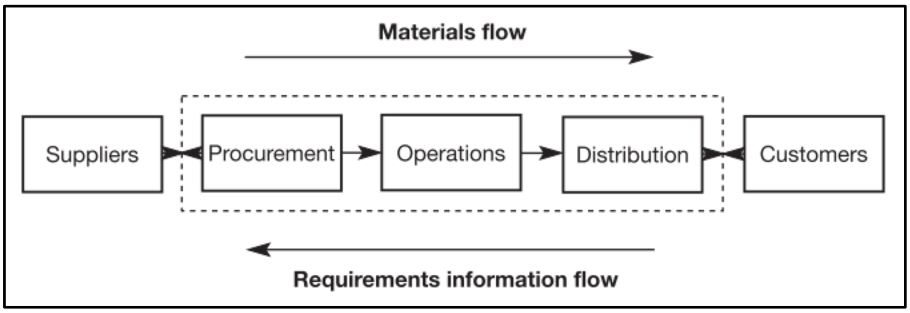


*Figure 1. Supply Chain system* (Christopher, 2011).

As it is possible to see, generically, the supply chain is composed by these five different stages. The suppliers, the procurement of essential raw materials, the operations that transform the raw materials into the final product, or service, that will then be distributed to the costumers. The idea supported by this work is that it is possible to make improvements in all these five stages of the supply chain, to reduce costs and gain competitive advantages. In this work in specifically the stage of the supply chain that is going to be in study is the distribution. Thereby, in the next chapter this one is going to be studied to understand what it is and where are the costs that can be cut out or, at least, reduced.

## 2.2. Distribution

The discussion in the previous sections of this chapter has presented the major stages found within a logistics or supply chain system. In sum, from a physical point of view, and according to Figure 1, a supply chain consists of several stages where items are produced, transformed, assembled, packaged and distributed to costumers (Brandimarte & Zotteri, 2007). Therefore, the fundamental characteristics of a physical distribution structure could be considered as the flow of material or product, combined at various points by periods when the material or product is stationary (Rushton et al., 2010). The stationary periods are usually for storage or to allow some transformation to the product.

### 2.2.1. Value-Adding Time

While the management of materials represents the storage and flows into and through the production process, distribution represents the storage and flows from the final production point to the customer or end user (Christopher, 2011; Rushton et al., 2010). There is, though, one aspect that makes distribution such a critical stage for any supply chain. This aspect is associated to a certain concept, being it the value-adding time. It is actually very simple, value-adding time is the time spent doing something that creates a benefit for which the customer is prepared to pay (Christopher, 2016; Kozakowska & Taljedal, 2017). For example, it is legitime to classify manufacturing as a value-added activity as well as the physical movement of the product and the means of creating the exchange. In this context, the old saying 'the right product in the right place at the right time' summarizes the idea of customer value-adding activities (Christopher, 2011). Thus, any activity that contributes to the accomplishment of that goal could be considered as value adding.

On the other hand, non-value-adding time is the time spent on an activity whose elimination would lead to no reduction of benefit to the customer but may be necessary to facilitate long-term value adding activities (Kozakowska & Taljedal, 2017). However, some non-value-adding activities are necessary because of the design or state of some processes, but they still represent a cost that should be minimized (Christopher, 2011).

The difference between value-adding time and non-value-adding time is crucial to an understanding of how logistics processes can be improved. For example, operations such as moving a pallet into a warehouse, repositioning it, storing it and then moving it out has added no value but has added considerably to the total cost (Christopher, 2011). In the distribution stage these are daily procedures and that is what makes this stage a critical one. With optimizations in these procedures, that do not add value to the final product, it could, then, be possible to reduce costs and improve profits.

### 2.2.2. Activities

For most organizations it is possible to establish a list of key areas representing the major activities of distribution. These will, commonly, include transport, warehousing, inventory, packaging and information (Mentzer et al., 2008; Rushton et al., 2010).

Transport includes elements such as the mode of transport, type of delivery operation, load planning and route schedule (Rushton et al., 2010).

Warehousing, on the other hand, deals with problems such as – location of warehouses, number and size of distribution depots, types of storage and the necessary materials handling equipment (Rouwenhorst et al., 2000; Rushton et al., 2010).

The inventory area, even if it is related to the warehousing, it is a more specific activity that answers questions such as what to stock, where to stock and how much to stock (Rushton et al., 2010). While the packaging component decides questions related to unit load, protective packaging and handling systems (Rushton et al., 2010).

Finally, the information area deals with the design of information systems, controls procedures and forecasts to make sure everything goes as planned (Rushton et al., 2010).

In terms of costs, the costliest element of distribution is the transport, mainly due to high fuel costs, followed by warehousing (Rushton et al., 2010). If a company aims to improve processes related to distribution, these two elements should be a starting point because, since they are the costliest ones, slight reductions could have large impacts on the costs.

In this work, the element of distribution that is going to be the target of study is the warehousing. It is a very important element for the industry sector in study and is the final element that connects the company and the costumers. So, to better understand what operations make part of the warehousing and which one is going to be in study, in the next chapter – the Problem Description – a more detailed approach is made under this subject.

### 2.2.3. Impact on Companies

Before concluding this chapter, there are still some aspects to underline about distribution's importance in the current days. In fact, in the past few years, the concern about this stage of the supply chain has grown and so has the necessity to control it. Not only in terms of effectiveness but also in efficiency (Amstel & D'hert, 1996; Barreto, Amaral, & Pereira, 2017; Mentzer et al., 2008). This means that companies are becoming to pay more attention to this area and now, they do not only must make things adequately, but, instead, they must do them better. Especially better than the competition.

A major development that has contributed to the need for more control in distribution is the fact that distribution has a vital importance in fulfilling customer service (Amstel & D'hert, 1996)). Besides, the market growth and aspects such as lead time, delivery reliability, globalization and the shortening of the life cycle of products have contributed to a more competitive world (Amstel & D'hert, 1996; Gundlach et al., 2006; Huang & Keskar, 2007) where the companies who succeed are the ones prepared for any challenge and unpredictability of the market. With these aspects combined and with the growing number of performance indicators available in the distribution sector (Amstel & D'hert, 1996; Rezaei, Hemmes, & Tavasszy, 2017; Seth, Deshmukh, & Vrat, 2006), it is no surprise why companies recently started to worry more about aspects such as transportation and warehousing. Specifically, in what concerns with reduction of costs and service levels improvement.

## 2.3. Warehousing

Warehouses are an essential component of any supply chain. Their major roles include: buffering the material flow along the supply chain to accommodate variability caused by factors such as product seasonality and/or batching in production and transportation; consolidation of products from various suppliers for combined delivery to customers; and value-added-processing such as pricing, labeling, and product customization (Gu, Goetschalckx, & McGinnis, 2007).

Generally, it is possible to distinguish two types of warehouses: the distribution warehouses and the production warehouses (Berg & Zijm, 1999; Rouwenhorst et al., 2000). A distribution warehouse stores a big variety of materials that are often from different suppliers and delivers to a certain number of costumers (Rouwenhorst et al., 2000). A production warehouse, on the other hand, stores either raw materials, semi-finished products and finished products, and it is located in a production facility (Berg & Zijm, 1999; Rouwenhorst et al., 2000).

The store functions or warehouse operations, particularly inventory management, have advanced in the last few decades due to the short product life cycles and more demand fluctuation. The performance parameters selected are for instance truck time at the dock, accurate receipts received, time from receiving to pick location, labor hours consumed per order, time from picked order to departure, among others (Tjahjono, Esplugues, Ares, & Pelaez, 2017). The creation and storage of inventory is a cost and to achieve high levels of efficiency, the cost of inventory should be kept as low as possible (Damand, Barth, & Lepori, 2017; Hugos, 2018). As it is possible to see in Figure 2, in the moments when the raw materials or the finished products are in stock there is usually no value added to the product.

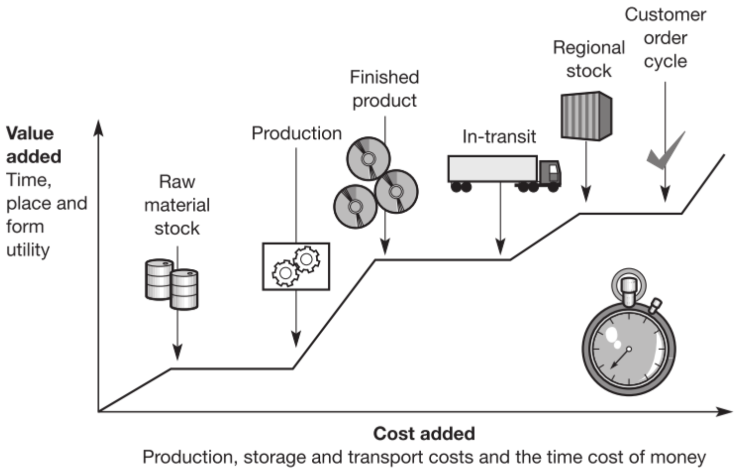


*Figure 2. Life cycle of a product* (Christopher, 2011).

The fact that the stock stages add no value to the product is the main reason why the price of stocks is so high, comparing to other logistics activities. While other operations, such as the production, add value to the final product, the creation of stock, adds no value while is costing a lot of money. However, in most of cases, warehouses and the inventory associated to them is necessary, for the reasons already mentioned above. So, it has been becoming an extreme important task to manage the warehouses in a way that the costs can be minimized. In this sense, there are some problems associated to warehouses. These problems are an example of what should be studied to reduce warehousing costs and still maintain the required inventory.

### 2.3.1. Decision-making Activities

According to Gu et al. (2007), a simple scheme to classify both warehouse design and operation planning problems is presented in Figure 3. This one summarizes the existing logistics' decision-making activities associated to warehouses.

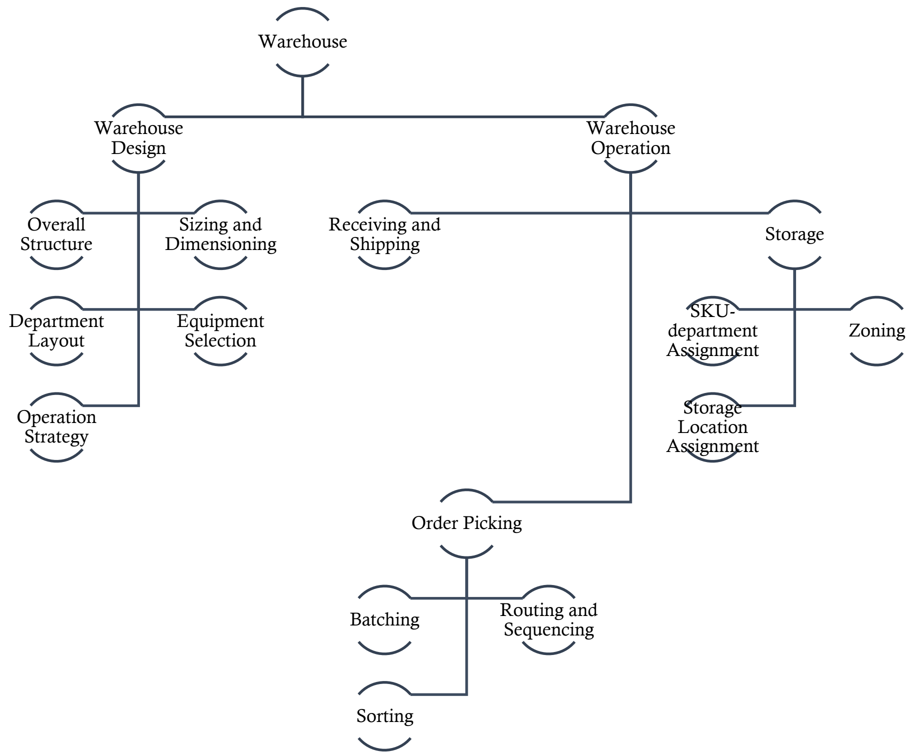


*Figure 3. Classification of the decision-making activities of the warehousing.*

In Figure 3 it is possible to verify that the two main general areas of decision-making activities related to warehouses are the design's area and the operations' area. The warehouse design area includes the choice of a layout for the four basic warehouse operations – receiving, storage, order picking and shipping (Berg & Zijm, 1999; Damand et al., 2017; Gu et al., 2007). This problem involves different stages of decisions and at each stage a certain number of performance metrics must be defined – cycle time, storage costs, etc. (Damand et al., 2017; Gu et al., 2007). What seems to be an easy task to accomplish, becomes a difficult one when, at each stage, commitments must be made between goals that are often contradictory (Damand et al., 2017). Another difficulty is the large number of possible layouts to apply at each operation's zone. Also, the design's decisions are linked to the type of warehouse that is in study. Depending on what type of warehouse is in study, there are different design criterions to take in consideration. For instance, if the target is the distribution warehouse some important criterions include the maximum throughput, while in a production warehouse includes, for example, the storage capacity (Rouwenhorst et al., 2000). The result of the design's decisions is going to have a lasting effect, since the layout is not something that changes daily.

The other area, the warehouse operations, on the other hand, is more related with strategic and more flexible decisions rather than definitive ones. This one includes operations such as receiving and shipping, storage and picking, as it is possible to see on Figure 3. Receiving typically involves the physical unloading of incoming transport and, in some cases, also includes activities such as unpacking, and repackaging, and quality control (Berg & Zijm, 1999; Rushton et al., 2010). While this operation brings products to the warehouse, there is the opposite one, the shipping, that loads outbound vehicles making the products leave the warehouse.

Inside the warehouse, there are two main operations, the storage and the picking. In the storage operation, products are usually taken to the storage area, which is, most of the cases, the largest space user in many warehouses (Gu et al., 2007; Rushton et al., 2010). The order picking, or just picking, is the operation of collecting a certain type and number of products before shipping, to satisfy the customer's request. About these two inside operations there is a high number of problems to solve such as the picking routing, picking batching and sorting, the storage layout and zoning, among others (Damand et al., 2017).

In this work, all the efforts of study are directed to the warehouse operation of receiving and shipping. Inside this thematic there are a lot of specific problems that must be considered. Some of these problems will be exemplified next, as well as the specification of which one is the target of this dissertation.

### 2.3.2. Receiving and Shipping

Receiving and shipping are the interface of any warehouse for incoming and outgoing physical flow. Incoming shipments are brought to the warehouse, unloaded at the receiving docks, and put into storage (Rouwenhorst et al., 2000). Orders are picked from storage, prepared and shipped to customers through shipping docks. Receiving and shipping operations involve, for example, the assignment of trucks to docks and the scheduling of loading and unloading activities (Gu et al., 2007; Rouwenhorst et al., 2000). Thus, associated to the operation of receiving and shipping there are other specific problems. Among others, it is possible to differentiate three: the truck-dock assignment; the order-truck assignment; and the truck dispatch schedule (Shipping) (Gu et al., 2007).

So, with information about things such as the incoming shipments – arrival time and contents; the customers' demands – orders and their expected shipping time; and the warehouse dock layout and available material handling resources (Gu et al., 2007), it is possible to make decisions about what strategies to adopt to avoid costs and delays. In this sense, the basic decisions in receiving/shipping operations can be summarized as:

(1) The assignment of inbound and outbound shippers – either client's shippers or supplier's shippers – to docks, which determines the total internal material flows;

(2) The schedule of the service of shippers at each dock. Assuming a set of shippers is assigned to a dock, the problem is like a machine scheduling problem, where the arriving shippers are the jobs to be scheduled;

(3) The allocation and dispatching of material handling resources, such as labor and material handling equipment (Gu et al., 2007; Rouwenhorst et al., 2000).

These decisions are usually subject to performance criteria and constraints such as:

- Resources required to complete all shipping/receiving operations;
- Levels of service, such as the total cycle time and the load/unload time for the shippers;
- Layout, or the relative location and arrangement of docks and storage departments;
- Management policies, e.g., one customer per shipping dock;
- Throughput requirements for all docks (Gu et al., 2007).

Considering the level of knowledge about the shipments, decision making in receiving and shipping can be distinguished in three different problems (Gu et al., 2007):

(a) No knowledge, other than warehouse layout;

(b) Partial statistical knowledge of arriving and departing processes, such as the average level of material flow from an incoming shipper to an outgoing shipper;

(c) Perfect knowledge of the content of each arriving shipper and each departing shipper (Gu et al., 2007).

In the scenario (a), it is not possible to have any basis for assigning carriers to docks, as well as it is not possible to precisely assign goods to storage locations. So, it is not clear in this case if there is any storage assignment rule that fits better than others. Usually, public warehouses can operate under this set of conditions, for example (Gu et al., 2007).

The second scenario is most common in company-owned or dedicated distribution warehouses and is the basis for most of the decision models in the literature (Gu et al., 2007).

The third, and last, scenario is becoming increasingly common through the application of advanced information technologies (Gu et al., 2007), as it is the one that aggregates all of the information needed to make more precise decisions.

In this work the general problem in study is the one stated in the point (2) – the schedule of the service of shippers at each dock, including the specific problems of dock-truck assignment and the dispatch schedule. In fact, the problem consists of scheduling, and is solved as a machine scheduling problem where the trucks/shippers are the jobs to be schedule. Also, the focus operation is the shipping, not including the receiving. Also, the warehouse in study is a production warehouse that is located outside the production line, so the final products enter the facility directly from the production line.

In the next section the concepts about the machine scheduling problem are going to be discussed to understand how this problem stated so far is going to be solved. In fact, there are two ways to solve this problem, the exact method and the heuristic one. What these two ways mean and what distinguish from one to another, are also the topics of the next section.

## 2.4. Scheduling

The problem in study is going to be treated as a Scheduling Problem, a Machine Scheduling Problem. But, before the real problem description itself and the modeling, there is some background that needs to be clarified.

Scheduling is a decision-making process that is used on a regular basis in many manufacturing and service industries. It deals with the allocation of resources to tasks over given time periods and its goal is to optimize one or more objectives (Pinedo, 2016c).

The resources and tasks in an organization can take many different forms. The resources may be machines in a workshop, runways at an airport, crews at a construction site, processing units in a computing environment, and so on. The tasks may be operations in a production process, take-offs and landings at an airport, stages in a construction project, executions of computer programs, and so on (Pinedo, 2016c). Taking in consideration this work, the resource is the warehouse while the task is the allocation of the clients. Each task may have a certain priority level, an earliest possible starting time and a due date. The objectives can also take many different forms. One objective may be the minimization of the completion time of the last task and another may be the minimization of the number of tasks completed after their respective due dates (Pinedo, 2016c).

About the scheduling of the shipping operation, very few formal models have been developed for the management of shipping as well as the receiving operations. Most of the literature that is available in this area addresses shipping and receiving operations and truck-to-dock assignment strategies for cross-docking warehouses (Gu et al., 2007). However, this work is not about cross-docking – considered a distribution warehouse – but instead, a production warehouse, as stated so far. So, with this study the goal is also to address some research about this type of problems, considering the lack of it in the current literature.

One thing that needs to be considered when discussing about scheduling is that the focus of any scheduling problem is the efficient allocation of one or more resources to activities over time (Chen, Potts, & Woeginger, 1998). Considering the Machine Scheduling Problem – a more specific problem of scheduling –, originally found in the manufacturing systems, a job consists of one or more activities, and a machine is a resource that can perform at least one activity at a time (Chen et al., 1998). The number of jobs is denoted by $n$ and the number of machines by $m$. Usually, the subscript $j$ refers to the job while the subscript $i$ refers to the machine (Pinedo, 2016c).

The Machine Scheduling Problem that is consider for this problem can be described as follows: there are $m$ machines that are used to process $n$ jobs. A schedule specifies, for each machine $i$ $(i = 1, \ldots, m)$ and each job $j$ $(j = 1, \ldots, n)$, one, or more, time intervals throughout which processing is performed on job $j$ by the machine $i$ (Brucker & Knust, 2012b; Chen et al., 1998). A schedule is feasible if there is no overlapping of time intervals corresponding to the same job (so that a job cannot be processed by two machines at once), and also if it satisfies various requirements relating to the specific problem type. The problem type is specified by the machine environment, the job characteristics and an optimality criterion (Chen et al., 1998).

### 2.4.1. Machine Environment

Different configurations of machines are possible. An operation refers to a specific period of processing by some machine type. It is possible to assume that all machines become available to process jobs at time zero (Chen et al., 1998).

In a single-stage production system, each job requires one operation, whereas in multi-stage systems the jobs require operations at different stages. Single-stage systems involve either a single machine, or $m$ machines operating in parallel. The case of a single machine is the simplest of all possible machine environments and is a special case of all other more complicated machine environments (Brucker & Knust, 2012b; Pinedo, 2016b). In the case of parallel machines three general cases can occur: identical parallel machines in which the processing time of job $j$ does not depend on the machine performing the job; uniform parallel machines in which the machines operate at different speeds but are otherwise identical; and unrelated parallel machines – the opposite of identical parallel machines, – in which the processing time of a job $j$ depends on the machine assignment (Brucker & Knust, 2012b; Chen et al., 1998; Pinedo, 2016b).

Regarding the multi-stage systems, or so-called shop scheduling problems (Brucker & Knust, 2012b), there are three main types to take in consideration. All such systems that are going to be consider comprise $S$ stages, each having a different function. In a flow shop with $S$ stages, the processing of each job goes through the stages $1,\ldots,s$ in that order (Brucker & Knust, 2012b; Chen et al., 1998). In an open shop, the processing of each job also goes once through each stage, but the routing (that specifies the sequence of stages through which a job must pass) can differ between jobs and forms part of the decision process (Chen et al., 1998). In a job shop, each job has a given routing through the stages – specific precedencies, and the routing may differ from job to job (Brucker & Knust, 2012b; Chen et al., 1998). There are also multiprocessor variants of multi-stage systems, where each stage comprises several (usually identical) parallel machines (Chen et al., 1998), becoming flexible job shop and flexible flow shop (Pinedo, 2016b).

Furthermore, a machine may be able to process several jobs, say $b$, simultaneously; that is, it can process a batch of up to $b$ jobs at the same time. In this context, the motivation for batching jobs is in the increase of efficiency since it may be cheaper or faster to process jobs in a batch than to process them individually (Potts & Kovalyov, 2000).The processing times of the jobs in a batch may not be all the same and the entire batch is finished only when the last job of the batch has been completed (Pinedo, 2016b). The definition of a batch is given as follows. The jobs are supposed to be partitioned into $F$ families, $F \geq 1$. A group of jobs belongs to the same family according to their similarity, so that no setup is required for a job if it belongs to the same family of the previously processed job (Potts & Kovalyov, 2000). Hereupon, a batch is defined as a set of jobs of the same family. While families are supposed to be given in advance, batch formation is a part of the decision-making process (Allahverdi, Ng, Cheng, & Kovalyov, 2008).

In addition, two types of batching machines are categorized in the literature: the serial batching machine and the parallel batching machine. On a serial batching machine, the length of a batch equals the sum of the processing times of its jobs (Baptiste, 2000). While on a parallel batching machine, the length of a batch equals the largest processing time of its jobs (Baptiste, 2000).

Batching models are further partitioned into batch availability and job availability models. According to the batch availability model, all the jobs of the same batch become available for processing and leave the machine together (Allahverdi et al., 2008; Potts & Kovalyov, 2000). For example, this situation is very common to occur if the jobs in a batch are placed on a pallet. In these cases, the pallet is only moved from the machine when all these jobs are processed. An alternative assumption is the job availability model, in which each job's start and completion times are independent of other jobs in its batch (Allahverdi et al., 2008; Potts & Kovalyov, 2000).

### 2.4.2. Job Characteristics

The processing requirements of each job $j$ are given: for the case of a single machine and identical parallel machines, $p_j$ is the processing time; for uniform parallel machines, the processing time on machine $i$ may be expressed as $p_j / s_i$ where $s_i$ is the speed of machine $i$; for the case of unrelated parallel machines, a flow shop and an open shop, $p_{ij}$ is the processing time on machine/stage $i$; and for a job shop, $p_{ij}$ denotes the processing time of the $ith$ operation (which is not necessarily performed at stage $i$). It is possible to assume that all $p_j$ and $p_{ij}$ are non-negative integers (Chen et al., 1998).

In addition to its processing requirements, a job is also characterized by its availability for processing, any dependence on other jobs, and whether interruptions in the processing of its operations are allowed (Chen et al., 1998; Meiswinkel, 2018). The availability of each job $j$ may be restricted by its integer release date $r_j$ that defines when it becomes available for processing, and/or by its integer due date $d_j$ that represents the completion date. Completion of a job after its due date is allowed, but then a penalty is incurred. When a due date must be met it is referred to as deadline and denoted by $\overline{d_j}$ (Chen et al., 1998; Meiswinkel, 2018; Pinedo, 2016b).

Job dependence arises when there are precedence constraints on the jobs. If job $j$ has precedence over job $k$, then $k$ cannot start its processing until $j$ is completed. Precedence constraints are usually specified by a directed acyclic precedence graph $G$ with vertices $1,...,n$. There is a directed path from vertex $j$ to vertex $k$ if and only if job $j$ has precedence over job $k$ (Chen et al., 1998; Pinedo, 2016b). Some scheduling models allow preemption: the processing of any operation may be interrupted and resumed at a later time on the same or on a different machine (Chen et al., 1998).

### 2.4.3. Optimality Criterion

Given a schedule $\sigma$, it is possible to calculate for job $j$: the completion time $C_j$; the flow time $F_j = C_j - r_j$; the lateness $L_j = C_j - d_j$; the earliness $E_j = \max\{d_j - C_j, 0\}$; the tardiness $T_j = \max\{C_j - d_j, 0\}$; and the unit penalty $U_j = 1$ if $C_j > d_j$, and $U_j = 0$ otherwise (Chen et al., 1998).

Some commonly used optimality criteria involve the minimization of the maximum completion time, or makespan, $C_{\max} = \max C_j$ – a minimum makespan usually means a good utilization of the machine(s); the maximum lateness $L_{\max} = \max L_j$ – it measures the worst violation of the due dates; the maximum cost $f_{\max} = \max f_i$, and the maximum earliness $E_{\max} = \max E_j$ (Chen et al., 1998; Meiswinkel, 2018; Pinedo, 2016b).

In case of weighted criterions, where the weight measures the importance of the job, some commonly used criterions are the total weighted completion time $\sum_j (w_j) C_j$; the total weighted flow time $\sum_j (w_j) F_j$; the total weighted earliness $\sum_j (w_j) E_j$; the total weighted tardiness $\sum_j (w_j) T_j$; the weighted number of late jobs $\sum_j (w_j) U_j$; or the total cost $\sum_j f_j$, where each maximization and each summation is taken over all jobs $j$ (Chen et al., 1998; Meiswinkel, 2018). Some situations require more than one of these criteria to be considered (Chen et al., 1998; Pinedo, 2016b).

### 2.4.4. Three-Field Representation

Considering all these aspects, a representation is needed to define any machine scheduling problem. So, it is convenient to adopt the representation scheme of (Graham, Lawler, Lenstra, & Kan, 1979). This is a three-field descriptor $\alpha | \beta | \gamma$ which specifies the problem type where $\alpha$ represents the machine environment, $\beta$ defines the job characteristics, and $\gamma$ is the optimality criterion (Allahverdi et al., 2008; Chen et al., 1998; Meiswinkel, 2018).

For $\alpha$ there is a possibility of combinations that can occur. This field takes the form $\alpha = \alpha_1 \alpha_2 \alpha_3$, where $\alpha_1$, $\alpha_2$ and $\alpha_3$ are interpreted as follows. If $\alpha_1 = \circ$, it means the problem deals with a single machine; if $\alpha_1 = P$: identical parallel machines; and if $\alpha_1 = Q$, $R$, $O$, $F$ or

$J$ uniform parallel machines, unrelated parallel machines, an open shop, a flow shop or a job shop, respectively (Chen et al., 1998; Meiswinkel, 2018).

For the $\alpha_2$ field there are only three different possibilities: if $\alpha_2 = \circ$ the number of machines/stages is arbitrary; if $\alpha_2 = m$ it means that there is a fixed number $m$ of machines; and last if $\alpha_2 = s$ that means that there is a fixed number $s$ of stages. Finally, the $\alpha_3$ element only exists if there are any stages on the process (Chen et al., 1998; Meiswinkel, 2018).

So, to conclude and taking into example a single machine problem, the $\alpha = \alpha_1\alpha_2\alpha_3$ would be represented as $\alpha = \circ 1 \circ$, or simply $\alpha = 1$ (Chen et al., 1998).

The second field $\beta \subseteq \{\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7\}$ indicates job characteristics. Excluding the $\beta_1$, that is related to the on-line concepts and on-list, typically all the other ones are characterized when describing a problem. Saying so, the other fields are described as follows: $\beta_2 \in \{\circ, r_j\}$ and defines the existence or not of the release dates, if jobs have release dates than $\beta_2 = r_j$. On the other hand, $\beta_3$ is destined to characterize the existence or not of the deadlines, following the same example of $\beta_2$. That said, $\beta_3 \in \{\circ, \overline{d_j}\}$, and in case of specific deadlines: $\beta_3 = \overline{d_j}$. The $\beta_4$ factor defines the existence or not of preemption. So, $\beta_4 \in \{\circ, pmtn\}$ and if preemption is allowed, $\beta_4 = pmtn$ (Chen et al., 1998; Meiswinkel, 2018).

The two parameters – $\beta_5, \beta_6$ – are the ones related to precedencies and processing times, respectively. In terms of precedencies, $\beta_5 = \circ$ if there is not any precedence constraint specified. In the case of specific precedencies $\beta_5$ can be equal to *chain, intree, outtree, tree* or *prec*. The meaning of each possibility is related to the way precedencies are defined. For example, in the case of $\beta_5 = prec$ it means that jobs have arbitrary precedence constraints (Allahverdi et al., 2008; Chen et al., 1998).

The processing times identified by $\beta_6$, can be equal to one out of three different ways. Saying so, $\beta_6 \in \{\circ, p_j = 1, p_{ij} = 1\}$, where $\beta_6 = \circ$ means that processing times are arbitrary; $\beta_6 = p_j = 1$ means that all jobs in a single-stage system have unit processing times (Chen et al., 1998; Meiswinkel, 2018); and finally $\beta_6 = p_{ij} = 1$ means that all operations in a multi-stage system have unit processing times (Chen et al., 1998).

The $\beta_7$ defines the existence, or not, of batching scheduling. A machine may be able to process several jobs, say $b$, simultaneously; that is, it can process a batch of up to $b$ jobs at the same time (Pinedo, 2016b). There three alternative values for $\beta_7$ (Dürr, Knust, Prot, & Vásquez, 2016). $\beta_7 = s-batch$, the batching machine is a serial batching machine which means that the processing time of a batch is the total processing time over all jobs in the batch (Baptiste & Jouglet, 2001; Dürr et al., 2016). $\beta_7 = batch(\infty)$, the machine is a parallel batch machine and there is no limit on the number of jobs in a batch and the processing time of a batch is the maximum processing time over all jobs in the batch (Dürr et al., 2016; Potts & Kovalyov, 2000). Last, $\beta_7 = batch(b)$, the batching machine is a parallel batch machine and the batch consists of a maximum $b$ jobs and its processing time is the maximum processing time over all jobs in the batch (Brucker et al., 1998; Dürr et al., 2016).

Lastly, the third field $\gamma$ defines the optimality criterion, which involves the minimization of $\gamma \in \{C_{\max}, L_{\max}, E_{\max}, T_{\max}, f_{\max}, \sum(w_j)C_j, \sum(w_j)F_j, \sum(w_j)E_j, \sum(w_j)T_j, \sum(w_j)U_j, \sum f_j\}$ (Allahverdi et al., 2008; Chen et al., 1998; Meiswinkel, 2018). As it was being said lately, it is sometimes appropriate to consider several of these criteria.

To finish this section and to illustrate the three-field descriptor, three examples are now presented: the $1|r_j, prec|\sum w_j C_j$ is the problem of scheduling jobs with release dates and precedence constraints on a single machine to minimize the total weighted completion time. The $R|pmtn|L_{\max}$ is the problem of preemptively scheduling jobs on an arbitrary number of unrelated parallel machines to minimize the maximum lateness (Chen et al., 1998). And finally, the third example, $P_m|r_j, d_j|\sum w_j T_j$ (Pinedo, 2016b) refers to a system with $m$ machines in parallel; job $j$ arrives at release date $r_j$ and has to leave by the due date $d_j$. If job $j$ is not completed in time a penalty $w_j T_j$ is incurred.

## 2.5. Methodologies

After understanding how the machine scheduling problem is characterized and defined, in this section, the main goal is to outline the methods and techniques that are used to analyze and solve scheduling problems.

In fact, a scheduling problem is not more than a special type of combinatorial optimization problem. Thus, it is possible to use methodologies already used for combinatorial optimization (Chen et al., 1998). In this sense, a significant research topic in scheduling as well as in combinatorial optimization is the use of *Complexity Theory* to classify scheduling problems as polynomial solvable or NP-hard.

About the complexity theory, generically it is a central field of the theoretical foundations of Computer Science. This field is concerned with the study of the intrinsic complexity of computational tasks. Therefore, a typical complexity theoretic study refers to the computational resources required to solve a computational task. Thus, computational complexity is the general study of what can be achieved within limited time and/or other limited natural computational resources (Goldreich, 2008).

About this matter, practical experience has shown that some scheduling problems are easier to solve than others. For example, computers of today can solve instances of problem $1 \; || \; \sum w_j C_j$ with several thousands of jobs within seconds, whereas it takes at least several hours to solve some even moderately sized instances of problem $J \, || \, C_{\max}$ with, for example, 30 jobs and 30 machines (Chen et al., 1998). So, in this sense, computational complexity theory provides a mathematical framework that is able to explain these "observations from practice" and that yields a classification of problems into easy and hard ones (Chen et al., 1998; Dorigo & Stützle, 2003). This mathematical framework is not relevant for this study so, about this matter the goal is only to understand that some problems are not easy to solve, even for computers, therefore sometimes it is necessary to have some techniques to overcome these difficulties. But, before the analysis of these techniques, it is important to distinguish the easy from the hard problems, even if in general aspects.

Let us start with a definition of an algorithm. An algorithm is a step-by-step procedure for solving a computational problem. For a given input $x$, it generates the correct output $f(x)$ after a finite number of steps. The efficiency of an algorithm for a given problem is measured by the maximum number of computational steps and time needed to obtain an optimal solution as a function of the size of the instance (Chen et al., 1998; Pinedo, 2016a).

This, in turn, requires a definition of a computational step. In practice, a computational step in an algorithm is either a comparison, a multiplication or any data manipulation step concerning one job (Pinedo, 2016a). The efficiency of an algorithm is then measured by the maximum number of computational steps needed to obtain an optimal solution (as a function of the size of the instance, i.e., the number of jobs). The number of computational steps may often be just the maximum of iterations the algorithm has to go through. Even if this number of iterations is typically approximated (Chen et al., 1998; Pinedo, 2016a).

In this sense, a problem is said to be *polynomial* if its time complexity is bounded by a polynomial input size (Chen et al., 1998); on the other hand, if that polynomial time is not verified, the problem is said to be NP-hard. The NP-hardness of a problem suggests that there are instances for which the computational time required to find an optimal solution increases exponentially with problem size. So, for NP-hard problems, what seems to happen is that it is not always possible to find an optimal solution quickly.

So, if large computational times for such problems are unacceptable, then, instead of searching for an optimal solution with enormous computational effort, a heuristic (method) or an approximation algorithm is used to give an approximate solution (Chen et al., 1998; Pinedo, 2016c).

In addition to exact methods for small instances, to obtain exact solutions of NP-hard scheduling problems, enumerative algorithms are usually applied. The main types of enumerative algorithms are branch and bound and dynamic programming, and both may benefit from dominance rules which help to restrict the search (Chen et al., 1998; Pinedo, 2016d). For many scheduling problems, metaheuristic methods including simulated annealing, greedy randomized adaptive search, *tabu* search and genetic algorithms are very successful in generating high-quality solutions (Berghman & Leus, 2015; Chen et al., 1998; Damodaran, Ghrayeb, & Guttikonda, 2013; Kadhim, Ali, & Kassim, 2018).

Resuming all these ideas, the main tools for providing negative results – meaning the non-existence of fast algorithms for a specific problem, – come from computational complexity theory. Also, the main tools for providing positive results are exact methods and enumerative algorithms for finding exact solutions and heuristic methods for finding approximate solutions. For this work the tools used for providing solutions were an exact method and two heuristic methods. Therefore, in the next sections these two subjects are going to be contextualized.

### 2.5.1. Mathematical Model

To solve a problem with exact methods, a mathematical model is usually developed. This in turn, when associated to optimization problems may become a linear programming model, if the function to minimize, as well as its constraints, are linear.

The linear programming subject is mainly concerned with the optimization – minimization or maximization – of a linear function, always having in consideration a set of linear equality and/or inequality constraints or restrictions (Bazaraa, Jarvis, & Sherali, 2010). Therefore, it is possible to condense the structure that characterizes a linear programming problem into the following form (Bazaraa et al., 2010; Lewis, 2008; Taha, 2007; Vanderbei, 2014):

| | |
|---|---|
| *max* or *min* | **Objective Function** |
| *subject to* | **Constraints** |

In a more mathematical approach, it is possible to summarize a linear programming model in the following notation (Bazaraa et al., 2010; Lewis, 2008; Vanderbei, 2014):

$$\begin{array}{lccccccccc} \text{Minimize} & c_1x_1 & + & c_2x_2 & + & \ldots & + & c_nx_n & = & z \\ \text{Subject to} & a_{11}x_1 & + & a_{12}x_2 & + & \ldots & + & a_{1n}x_n & \geq & b_1 \\ & a_{21}x_1 & + & a_{22}x_2 & + & \ldots & + & a_{2n}x_n & \geq & b_2 \\ & \vdots & & \vdots & & & & \vdots & \vdots & \vdots \\ & a_{m1}x_1 & + & a_{m2}x_2 & + & \ldots & + & a_{mn}x_n & \geq & b_m \\ & x_1, & & x_2, & & \ldots, & & x_n & \geq & 0. \end{array}$$

Note that in this case the constraints considered are inequalities (≥), but they can be either equalities or inequalities. The next relation sums up this idea (Vanderbei, 2014):

$$a_1x_1 + a_2x_2 + \ldots + a_nx_n \begin{Bmatrix} \geq \\ = \\ \leq \end{Bmatrix} b$$

So, and subtitling the notation presented so far, in linear programming, $z$, the expression being optimized, is called the objective function. Plus, the variables $x_1, x_2, \ldots, x_n$ are called decision variables, the ones to be determined (Bazaraa et al., 2010; Lewis, 2008). Last, but not least, the coefficients $c_1, c_2, ..., c_n$ are known as cost coefficients and the coefficients $a_{ij}$ for $i = 1, ..., m$; $j = 1, ..., n$ are called the technological coefficients (Bazaraa et al., 2010).

Any solution of the model is feasible if it satisfies all the constraints (Lewis, 2008; Taha, 2007). However, it is only optimal if, in addition to being feasible, it yields the best – maximum or minimum – value of the objective function (Taha, 2007). However, even if linear programming models are designed to "optimize" a specific objective criterion subject to a set of constraints and can achieve in fact the best solution, that does not ensure the quality of the resulting solution for the practical problem. In fact, the quality highly depends on the capacity of the model in representing the real system (Taha, 2007).

The linear programming model becomes an Integer Linear Programming (ILP) model if all the variables are restricted to be integers. If the optimization problem involves continuous and integer variables, then the linear programming model becomes a Mixed Integer Linear Programming (MILP) model (Pochet & Wolsey, 2006).

Considering the amount of constraints and variables and the length of the input information, a computer solver is going to be used to solve the MILP model. To have access to commercial solvers, internet platforms are usually used, one example is the NEOS Server. The NEOS Server is a free internet-based service for solving numerical optimization problems (Wisconsin Institutes for Discovery, 2018). Hosted by the Wisconsin Institute for Discovery at the University of Wisconsin in Madison, the NEOS Server provides access to more than 60 state-of-the-art solvers in more than a dozen optimization categories (Wisconsin Institutes for Discovery, 2018), for academic and scientific purposes. To submit a model – usually named job – in the NEOS Server, a modeling language is needed. In this sense, one example of a modeling language is the AMPL – A Mathematical Programming Language. AMPL closely resembles the symbolic algebraic notation, already mentioned, that many modelers use to describe mathematical programs (Fourer, Gay, & Kernighan, 1990). Still, it is regular and formal enough to be processed by a computer system (Fourer et al., 1990).

While AMPL creates optimization problems from models and data, and retrieves results for analysis, solvers are the number-processing algorithms that compute optimal solutions (AMPL Optimization Inc., 2018). There are several solvers that can solve specific linear optimization problems, the so called LP-solvers (Meindl & Templ, 2013). Available LP-solvers differ in many ways. They come with different licenses and features, for instance, different solvers may contrast in terms of how problems can be specified (Meindl & Templ, 2013). Among the most popular solvers is the *Gurobi*. Since it is beyond the scope of this project to enumerate more solvers and describe them, the Gurobi was the one being used to solve the mathematical model. Saying so, and just briefly presenting this solver, the Gurobi Optimizer is seen as a modern solver for linear as well as other related (non-linear, e.g.) mathematical optimization problems (Meindl & Templ, 2013).

### 2.5.2. Heuristic Methods

The knowledge that a scheduling problem is considered NP-hard brings no consolation when the goal is to solve the problem. Therefore, after understanding how mathematical models can be modeled and processed, to obtain both feasible and optimal solutions, it is now time to realize how these mathematical models can be "transformed" into approximate algorithms. Often, approximate algorithms are the only feasible way to obtain near optimal solutions at relatively low computational cost (Dorigo & Stützle, 2003). However, there is not any recipe to turn a mathematical model in an approximation algorithm so, in this case the word "transform" is used in a figurative way. In fact, "transform" in this case only means to create an algorithm capable to incorporate the objective function and all its constraints but, without needing to cover all the feasible solutions that an exact algorithm usually covers (Brucker, 2004b).

Heuristic algorithms are often applied to determine solutions that hopefully are not too far away from the global optimum (Brucker, Hurink, & Werner, 1997). Among the reasons that justify the large utilization of heuristics in operations research, it is possible to highlight the fast results (Brucker, 2004b; Silver, 2002). However, even if the main usage of the word "heuristic" is mostly the adjective of "improving problem solving", there might also be a slightly negative meaning attached to it (Groner & Groner, 1983). In fact, between the main disadvantages of a heuristic method is the lack of a good solution guarantee (Brucker, 2004b; Groner & Groner, 1983). That happens because the quality of a solution is directly attached to the quality of the heuristic's method. So even if the modern picture of a search for the solution is intelligently directed, there is still an inherent uncertainty (Aickelin & Clark, 2011; Groner & Groner, 1983). Thus, giving this context, a possible generic definition associated to the concept of heuristic might simply be any approach without formal guarantee of performance (Brucker, 2004b).

Most heuristic algorithms used are either constructive algorithms or local search algorithms (Dorigo & Stützle, 2003). However, these two types of methods are significantly different. Considering the constructive algorithms, these type of heuristic algorithms build solutions in an incremental way starting with an empty initial solution and iteratively adding appropriate solution components without backtracking until a complete solution is obtained (Dorigo & Stützle, 2003). For example, the construction of a first solution following a simple rule such as the Earliest Due Date (EDD) is a constructive algorithm. The main advantage of constructive algorithms is that they are typically the fastest approximate methods (Dorigo & Stützle, 2003). However, the solutions they generate are not of a very high quality and they are not guaranteed to be optimal with respect to small changes (Dorigo & Stützle, 2003). Giving this first solution for a problem a constructive algorithm provides, another common heuristics that arises and, one of the most successful methods for getting rid of hard combinatorial optimization problems is the discrete equivalent of "hill climbing", currently known as local (or neighborhood) search (Brucker, 2004b; Brucker et al., 1997; Brucker & Knust, 2012a; Dorigo & Stützle, 2003).

Local search is an iterative procedure which moves from one solution to another as long as necessary (Brucker, 2004b). The procedure of a typical local search algorithm is to explore the search space of complete solutions, in order to find better feasible solutions (Dorigo & Stützle, 2003). The search space is known as neighborhood structure. To implement local search it is necessary to define a base solution and a neighborhood structure (Brucker & Knust, 2012a; Dorigo & Stützle, 2003; Sampson & Weiss, 1993). To create the neighborhood structure a certain move, or more than one, are applied to a given solution. The quality of the final solution achieved is directly related to the moves applied to obtain the final neighborhood structure. So, it is possible to conclude that the choice of a suitable structure has some important influence on the quality of the search algorithm (Brucker et al., 1997; Dorigo & Stützle, 2003; Sampson & Weiss, 1993). In sum, a local search procedure can be defined by the next four steps (Sampson & Weiss, 1993):

(1) The construction of a primary solution as the base solution, using arbitrary methods or constructive algorithms, for example;

(2) The changing of the base solution accordingly to the neighborhood structure;

(3) If the changed solution provides a better objective function value than the base solution, then the changed solution becomes the base solution;

(4) Start again at step 2 until no improving neighbor solution can be found.

Usually these steps are repeated until no improving neighbor solution can be found in the neighborhood of the current solution and the algorithm ends in a local optimum (Dorigo & Stützle, 2003).

Besides constructive algorithms and local search, another type of heuristic method is the metaheuristics. Metaheuristics are powerful algorithmic approaches which have been applied with great success to many difficult combinatorial optimization problems. An advantage of metaheuristics is that they can easily handle the complicating constraints found in real-life applications (Gendreau & Potvin, 2005).

In the term metaheuristics, first introduced by (Glover, 1986), the prefix *meta-* means "beyond" or "higher level." This type of heuristic algorithms usually perform better than simple heuristics (Dorigo & Stützle, 2003; Gandomi, Yang, Talatahari, & Alavi, 2013; Yang, 2011). All metaheuristic algorithms use some trade-off of local search and global exploration. The variety of solutions is often realized via randomization (Gandomi et al., 2013). What this randomization is good for is to provide a method to move away from local search and instead look for a more global scale search (Gandomi et al., 2013).

The main components of any metaheuristic algorithm are: intensification and diversification, or exploitation and exploration (Blum & Roli, 2003). Diversification means generating diverse solutions so as to explore the search space on the global scale (Gandomi et al., 2013). On the other hand, intensification means focusing on the search in a local region by exploiting the information that a current good solution is found in this region (Gandomi et al., 2013; Yang, 2011). The diversification via randomization increases the diversity of the solutions while keeping the solutions from being stuck at local optima. The good combination of these two major components will usually ensure that the global solution is achievable (Gandomi et al., 2013).

Summarizing and concluding metaheuristic's topic, it is possible to outline some fundamental characteristics, being them (Blum & Roli, 2003; Gandomi et al., 2013; Osman & Laporte, 1996):

- Metaheuristics are strategies that "guide" the search process;
- Techniques which constitute metaheuristic algorithms range from simple local search procedures to complex learning processes;
- Metaheuristics are approximate and usually non-deterministic;
- Metaheuristic algorithms may incorporate mechanisms to avoid getting trapped in confined areas of the search space;
- Today's more advanced metaheuristics use search experience (using memory) to guide the search.

To conclude this section, it is relevant to notice that when evolving from construction algorithms, to local search and lately to metaheuristics, the level of complexity and the time needed to solve the problem grows. On the other hand, it is likely to find a better solution using a metaheuristic than a construction algorithm. Nevertheless, any heuristic algorithm is usually (or always), faster than a mathematical program, or exact method, because, as it was already mentioned, heuristic methods do not cover all feasible solutions. When solving a problem, it is important for the expert to analyze all the possibilities of resolutions in order to find the one that generates good solutions with the lesser number of resources needed.

# 3. Problem Description

The problem in study arises in the cement industry. To begin this new chapter, a global overview of this industry is going to be presented. After this, the real problem itself is going to be descripted and some assumptions will be established. Finally, before ending this chapter, three different ways for formulating the problem will be presented, however, only one of them is going to be extended for the chapter *4 – The Methodology*. These three ways are different because some problem specifications differ from one to another. The one that is going to be adopted to solve the problem, is the one that best approaches the formulation of the problem from the reality.

## 3.1. Cement Industry – Global Overview

Cement being the second most consumed substance in the world, after water, is an irreplaceable ingredient in a vast majority of applications (Amrina & Vilsi, 2015; Noche & Elhasia, 2013). It is the glue of concrete and the most massive manufactured product by human society with the largest materials flow in the world and the basic ingredient for the construction industry (Elhasia, Noche, & Zhao, 2013; Selim & Salem, 2010; Shen et al., 2017). For instance, constructions such as civil infrastructure projects, houses, power generation plants and many more cannot be built without cement (Noche & Elhasia, 2013).

The consumption of cement, in return, is closely linked to both the state of economic development in any given country or region and to the economic cycle (Noche & Elhasia, 2013). In some more developed markets the cement sales are dependent on the growth and habits in the construction sector, a sector that is itself following very closely the economic situation prevailing (Noche & Elhasia, 2013). The fast industrialization and urbanization of the current world calls for more and more infrastructures, highways, rail ways, and being cement the main construction material, the demand of this product keeps increasing quickly (Shen et al., 2017). So, allied to both economic and population growth (Roser, 2018; Roser & Ortiz-Ospina, 2018), the production of cement worldwide is growing too, as it is possible to verify in the Figure 4.

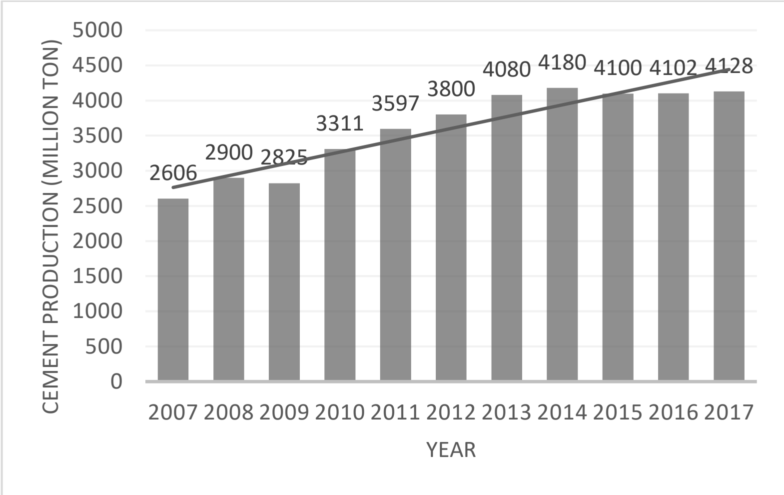


*Figure 4. World cement production over the past 10 years. Data source:* (USGS, 2018) - *Cement Statistics and Information.*

Even if this growth of the cement production is a good sign for companies in this sector, because the demand is getting bigger, there are still many challenges to overcome. Sustainable manufacturing, for instance, is certainly one of the critical issues for the cement industry (Amrina & Vilsi, 2015; Selim & Salem, 2010). Sustainable manufacturing, on the other hand, can be defined as the creation of manufactured products that minimize negative environmental impacts, preserve energy and natural resources, are safe for employees, communities and consumers (Amrina & Vilsi, 2015). The general principle of sustainable manufacturing is to reduce the intensity of materials use, energy consumption and emissions, while maintaining, or improving, the value of products to society and to organizations (Amrina & Vilsi, 2015).

Besides the sustainability, studies reflect that the two other major concerns of the cement industry include the manufacturing process itself and the cement material management (Agudelo, 2009; Elhasia et al., 2013). While the manufacturing process does not match the scope of this project, the cement material management on the other hand can clearly be included in the supply chain management and the logistics of the cement industry (Agudelo, 2009). However, it is only a part of the SCM which for itself is already a topic with limited research in the cement industry. In the meantime, while topics such as distribution and transportation are also addressed in the current literature (Agudelo, 2009), there is not much information about them (Elhasia et al., 2013; Fonseca et al., 2018). With this work the aim is also to address more information concerning the supply chain management in the cement industry, specifically in what concerns the distribution process. A simple scheme that can illustrate the cement supply chain is evidenced in the Figure 5.

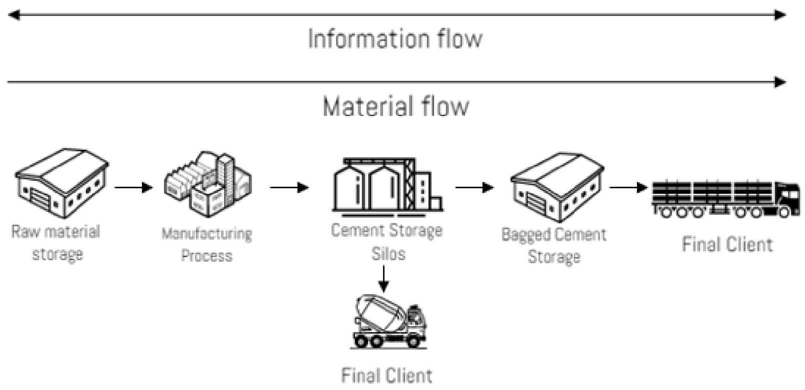


*Figure 5. Cement supply chain scheme.*

The first operation of the cement supply chain includes the purchase and storage of raw materials. Cement plants are frequently located near the quarries which are the source of their main raw materials (Agudelo, 2009). After the manufacturing process, the cement is moved to storage silos. Then, two things can happen because of the cement as a final product being sold both as a bulk product or in bags. In the first situation the cement reaches the final client, through bulk trucks, and in the second one the cement is bagged and lately storage until a customer places an order.

The distribution process in the cement supply chain shows up in both bulk and bag cement delivery and there are physical characteristics about the cement that challenge this distribution process (Agudelo, 2009). Besides the fact that cement is a heavy and bulky load, which hinders the process of moving the cement, it also has low-cost prices (Agudelo, 2009; Rushton et al., 2010). Among others, these are the characteristics that make the relative costs of cement's logistics very high (Rushton et al., 2010). So, with certain improvements on the cement distribution operations, costs can be reduced, service levels improved and, consequently, a more sustainable industry might be achieved.

## 3.2. The case study

The case study of this work is inserted in the UH4SP project. The UH4SP was born in a Portuguese company that provides a management software for other companies. In this case, these other companies are, mostly, cement ones. In a typical cement plant, the cement manufacturing facility is linked to the distribution one. After the operation of processing the cement, this one is stored in silos or bagged and then stored in a distribution warehouse. However, it is also frequent to have cement plants that do not include the manufacturing facility. These ones usually only contain cement silos and distribution warehouses of bagged cement. In this specific case of no manufacturing plants the only purpose of the plant is the distribution operations. Despite the fact of the existence or not of the manufacturing facility, the distribution process in cement plants always exist.

Regarding the current state of the processes that appears in every plant of the cement industries in study, there are usually five steps. First, when a client arrives to the cement facilities he needs to check in. Next, he will wait for being called to enter, in the parking lot. After waiting he will enter through, usually, one of two different entries. In one of them there is the process of weighing and in the other one there is not. Usually the clients that do not need to be weighed are the bulk trucks. All the others, both to enter and to leave the cement plant, must be weighed, for control and security purposes. Following the entry on the facility the client is going to drive to the place that brought him to the cement plant. If he wants bagged cement he is going to the warehouse, if he wants bulk cement then he is going to the cement silos and, finally, if he is not a client but else a provider, he is going to the raw material warehouse to leave the products. Concluding his specific process, the client is finally ready to leave the cement facility.

For this work the only clients that are going to be scheduled are the ones that request bagged cement, since the distribution process in study is the distribution of bagged cement. In the next section this distribution process is going to be descripted, as well as what are the real problems that are happening that are causing troubles to both the cement company and its clients.

### 3.2.1. Cement Storage System

In the cement plants in study, the warehouses work as distribution centers. They store the bagged cement and the customers go directly to the warehouse's facility to pick their order, by truck. For each warehouse there is a certain number of docking bays. A docking bay is a limited space of the warehouse where the client's truck can stop to load its order. An order is fulfilled only through the companies' resources. They might be manpower or other type of material handling equipment such as forklifts. They usually are forklifts. The number of resources is equivalent to the loading rate at each moment. The more resources exist, the faster is the loading process. On the other hand, the number of docking bays of each warehouse is equivalent to its length. Usually the length of the warehouse does not follow the number of resources available. So, if a certain warehouse has a bigger length than another, that does not mean it has more resources.

These two characteristics – the length and the number of resources – of the warehouses are the most important for this problem in study. Of course, there are other specifications such as the level of stock of the warehouse, however, in this specific case study the level of stock is given as being always enough to fulfill all the demand.

Giving this background, the main question now relies on what is happening in the reality that causes trouble to both the cement company and its clients. The problem is primarily in the lack of information and organization through all the supply chain. Allied to this, there is the nonexistence of specific priority dispatching rules for the process of scheduling the clients/trucks. The combination of these problems brings nothing but long queues in the parking lot, delays and inefficient use of the resources. For example, with no scheduling models and with the lack of information through the different entities in the supply chain, what happens is that sometimes there is an opportunity to fulfill an order but there is not any information that both the resource of the warehouse and the docking bay is available. On the other hand, in some cases what happens is that for not knowing if there is not any docking bay or resource available the trucks start entering the facility and are directed to the warehouse. When they arrive at the warehouse they realize it is full and must wait in the roads of the cement plant causing congestions and consequently delaying other clients that must use that road.

With all these problems a necessity of improvement and optimization arises. Considering this conclusion, a scheduling model appears to be a good solution to work around these problems. In fact, besides the necessity to promote the trade of information through the supply chain, a scheduling procedure is also necessary to overcome problems such as inefficient use of resources and the delays. In the next section some specifications and assumptions will be stablished to create a scheduling model capable of solving most of the problems already mentioned.

### 3.2.2. Problem Specifications

Before initializing the process of scheduling the clients to the warehouse some assumptions were established. First, a warehouse is seen as a set of four main characteristics. These ones are the number of docking bays, the number of resources and the number and type of different products available and their positions relatively to the docking bays of the warehouse – which will directly interfere with the loading rate at each docking bay. The docking bays might be closer to a certain type of product and distant from another. That means that the products are spread through the warehouse but grouped per type of product. This implies that, when choosing the docking bay that each client must go, it will be better to choose the one that is closer to the product demanded. That way the loading rate will be greater. In addition, in some warehouses, several forklift trucks move the pallets and place them inside the trucks. In other ones, depending on the country and level of technology, rather than forklift trucks, it is the workers that move the cement bags and place them inside the costumer's trucks. In this study the only warehouses considered are the ones whose resources are forklift trucks. However, the only thing that changes in these two different scenarios is the loading rate. The loading rate is measured in number of material transported per unit of time. If the warehouse's resource is a forklift, this rate is going to be bigger than the case where the warehouse's resource is a worker. Besides, there is one more characteristic about the forklifts that is important to considerate. In some warehouses the operation of loading one truck can be done by more than one forklift. It is important to have this in consideration because it will interfere with the loading rate. If two forklift trucks are loading one truck in simultaneously then the loading rate is bigger than in the case where there is only one forklift. This is another technical feature of the warehouse because it will differ from one to another. In some warehouses it will be possible to have one truck being loaded by more than one resource and in others it will not.

Besides these characteristics of the warehouses there are the ones about the clients. Globally, the clients are characterized by the type and the quantity of product they order, their release dates and due dates. With this information and the information about the warehouse, it is possible to build a schedule capable of satisfying both the costumers and company restrictions. This schedule will also add more organization to the cement plant and, also, possibly reduce delays and the waiting time in the parking lot. Also, with the entire knowledge of where the costumers at each time of the process are and what resources are being used, it will be possible to improve the efficiency of the resources themselves. The case where it would not be possible to know if a resource was available to be use, with the scheduling model, hopefully, will not happen again.

In the next section three different ways to solve this scheduling problem will be exposed. In the end only one of them will be used. However, it is important to notice that all the three can be used depending of the technical features of the warehouses in study.

## 3.3. Problem Formulation

Three main different warehouse configurations were distinguish considering the range of cement industries in study. In the first one, the warehouse has more than one docking bay but only one forklift truck. In the second configuration the warehouse has equally more than one docking bay but in this case it has more than one forklift truck but less than the number of docking bays. In the third and last configuration the number of docking bays and the number of forklifts are the same and more than one. Different configurations ask for different ways of solving the problem. Therefore, if the warehouse has only one forklift truck it can be solve as a single machine scheduling problem, if it has more than one forklift but less than the number of docking bays it can be solve as a batch scheduling processing problem and, last, if the number of forklifts is equal to the number of docking bays it can be solve as a parallel machine scheduling problem. In these considerations it is assumed that one forklift can only load one truck at a time. For the case of parallel machines, for example, if one forklift could load more than one truck at the same time, then the problem could be solved as a shop floor problem. These ways of solving the problem are only suggestions and even if other ones could be presented, these were the ones that were thought to be closer to the reality having in consideration the case study.

### 3.3.1. Single Machine

A single machine scheduling problem can be described as follows: there are $n$ jobs $j_1, j_2, ..., j_n$ to be processed on a single machine – only processes one job at a time. For the problem under consideration, all jobs are non-preemptive.

In this case the jobs are the clients that ordered bagged cement and the machine is the warehouse. As in this case there is only one forklift available to fulfill all the orders, the warehouse works as a single machine since it can only process one job at a time. Depending on the cement type requested, the docking bay that is going to be used differs.

This kind of situation is found in small distribution centers where the number of docking bays itself is small too, usually more than one but less than six docking bays. The fact that these distribution centers are small explain the reason of only having one forklift available. The forklifts usually need space to maneuvering and if there is not enough space, then there is no reason to have more than one resource available, or else it would only delay the work. These small distribution centers exist but they are not very common considering the range of cement industries under study. So, this single machine scheduling could be a good approach to solve this problem in these small distribution centers, but since these are not the most common type of distribution centers, this approach remains here like a suggestion only, for possible enthusiastic on the matter.

### 3.3.2. Batch Processing Machine

In some scheduling applications, sets of jobs must be grouped into batches. A batch is a set of jobs which must be processed jointly on a machine. A batching problem is to group the jobs into batches and to schedule these batches (Brucker, 2004a).

In this case the jobs are the clients that need to be schedule and the machine is the warehouse. The difference considering the past formulation of the single machine problem is that in this case the warehouse can process more than one job at a time, because of having more than one forklift. The number of forklifts limits the minimum number of jobs in a batch and the number of docking bays the maximum one.

Batching problems have been identified by adding the symbol "s-batch" or "p-batch" to the $\beta$ -field of the classification scheme. For p-batching problems (s-batching problems) the length of a batch is equal to the maximum (sum) of processing times of all jobs in the batch. $\beta_6 = p - batch$ or $\beta_6 = s - batch$ indicates a batching problem. Otherwise $\beta_6$ does not appear in $\beta$ (Brucker, 2004a).

This type of situation is the most common considering the total number of cement industries in study. It frequently appears in cement industries with medium distribution centers where the number of docking bays varies between six and fifteen. As this configuration is going to be the focus of this work, in the next chapter a more detailed description is going to be presented.

### 3.3.3. Parallel Machine

A parallel machine scheduling problem can be described as follows: there are $m$ machines in parallel where machines may be identical ($P$), or have different speeds or uniform ($Q$), or completely unrelated ($R$). Each job can be performed on any of the machines (Allahverdi et al., 2008).

For this specific case of study, the machines would be the forklifts, available in each docking bay, and the jobs would be the clients to be scheduled. This type of situation appears in big distribution centers where almost all the processes are already automated and where the rate of arrival of the trucks is constantly and high. This kind of situation is not very commonly found however it exists and in some cases the amount of resources – equivalent to the number of docking bays – is more than enough to fulfill the orders. In fact, what happens sometimes is that the resources are way much more than what is needed, and their efficiency is lower than in other situations. Yet, there are also other situations where the number of resources is more than needed giving the demand in the specific case.

In sum, this kind of situation appears in some cement industries and when it happens, it is usually on big distribution centers – usually with more than fifteen docking bays –, with high demand associated. However, since the total number of cement industries in study does not include many big distribution centers, this type of interpretation, as in the single machine formulation, stays only as a suggestion for future work.

# 4. Methodology

The scheduling problem that is going to be presented in detail in this chapter arises in the warehouses in cement companies involving the scheduling, dispatching and assignment of truck loading operations. The purpose of this study is to start modelling the truck loading operations as a batch processing problem with serial batch scheduling and with restrictions in the batch capacity.

A procedure based on a mathematical algorithm was developed to sequence the dispatch of trucks and to assign trucks to docking bays, on the warehouses inside the plants. Based on the limitations of the exact method, two heuristic methods were also developed. In the next sections these three models will be presented but, before that, both the background of the real problem and the specifications of the batch processing problem will be considered.

## 4.1. Background Situation

In this study it is consider the problem of scheduling the truck loading operations in a cement industry warehouse. The truck loading operation happens when the costumer's trucks come to the cement plant and pick up their requests through the assistance of the company's forklifts. Each costumer has its own material request and availability during the day. To fulfil all the requests, there is only one warehouse available, with a limited number of resources (forklifts), and that is why there is some difficulties in programming when and to what docking bay, the trucks should be assigned to.

Due to this difficulty concerning the planning and scheduling of the trucks to the warehouse, the queues of clients waiting outside the cement plant become larger during the day. Additionally, and because of the long wait queues, the resources efficiency decreases because at some point they stop working, waiting for some client to arrive. On the other hand, the next client cannot reach the free docking bay because the lack of organization is so big that when a client leaves a docking bay it is not perceptible for the other ones waiting. This phenomenon causes delays and increases the idle time of the warehouse's resources.

Considering this background situation, an algorithm was developed for assigning jobs (costumers) to batches and then sequencing batches to minimize the makespan for all jobs. But, before the analysis of the algorithm, in the next section, some aspects about the batch processing problem considered in this study will be presented.

## 4.2. Batch Processing Problem

In the literature there are several reasons to justify the motivation for grouping batches. It may come, for instance, from the capability of the machine to process several jobs at once, as Webster & Baker (1995) illustrate. Imagine that jobs must be placed in an oven, for a heat-treat or a burn-in operation. The oven has a finite capacity, so that several of the jobs can be processed simultaneously. As in baking cookies, a group of jobs processed together is called a batch, and the model is called a batch processing model. Typically, the capacity of the oven is related to the weight, size, or the number of jobs in a batch. To the specific case of study of this work, the oven is the warehouse that has a limited number of resources, that consequently limits its capacity, and the jobs, or the cookies as mentioned in the last example, are the costumer's trucks that need to be loaded.

As Albers & Brucker (1993) underline, batching problems present a fruitful research direction and their solution enhances the ability to manage operations efficiently. This is one of the motivations to transform this problem in a batching problem and, also, because the results, obtained using batching scheduling, usually lead to improvement of resource usage and customer satisfaction which are important objectives for this work. Additionally, it was perceptible that there is not much, or even none, research in the application of batching models in this kind of problem of scheduling trucks to the warehouse so, this study shows innovation and, hopefully, inspires other researchers to investigate this problem following this point of view.

As the scheduling and assignment of trucks to docks is part of the decision making problem, so is the batch formation (Allahverdi et al., 2008). Which job is going to group with which other ones becomes now a part of the problem and, besides that, so does the order dispatch of each batch. Batch models are further partitioned into batch availability and job availability models. According to the batch availability model, all the jobs of the same batch become available for processing and leave the machine together. In the job availability model, each job's start and completion times are independent of other jobs in its batch (Allahverdi et al., 2008; Yuan, Liu, Ng, & Cheng, 2006). For this problem the model that is going to be used is the batch availability. Jobs that belong to the same batch start and complete the loading process at the same time. Giving these features and to solve this scheduling problem, some assumptions must be taken. In the next section these assumptions will be presented.

## 4.3. Problem Definition

In almost every problem, and more specifically in the case of scheduling problems, assumptions must be made to transform the real problem into a feasible problem. These simplifications of the real problem, or assumptions, are important because they allow us to simplify the problem and focus only on what is important to optimize or to solve. Therefore, and before the problem formulation, it is important to recognize some aspects.

First, all clients arrive to the cement facilities by truck. Each client has a specific request and release date. Each request is composed by the type of product the client wants and its quantity. The quantity of product – bagged cement – is measured in number of pallets. Plus, the clients enter the warehouse in group. These groups of clients are called batches and each batch has a minimum and a maximum number of clients. The minimum number of clients is given by the number of forklifts available in the warehouse and the maximum number is given by the number of docking bays. This means that, if the number of clients in the batch is the minimum one, each client is being served by each one of the forklift trucks. This is only possible because each client can only be serviced by one forklift at a time to easy the mobility of the forklifts inside the warehouse and to prevent possible incidents. Such as possible damage on the products and accidents with the workers, due to possible collisions of forklift trucks. On the other hand, when the length of the batch is more than the minimum, this means that the forklift trucks are loading simultaneously all the client's trucks. Concluding, when the clients enter the warehouse they are served by the total number of forklifts available, with at most only one forklift per client, at the same time, and which forklift is servicing which client, does not cover the focus of this study. Because of these assumptions related with the forklift trucks, the processing time is given by batch instead of by client. Plus, it is assumed that clients of the same batch enter and leave the warehouse at the same time, what turns the batch processing into a serial batch processing problem with restrictions in the batch capacity.

Regarding the warehouse there are also some assumptions that must be established. First, the stock associated to the warehouse is given as "unlimited". This means that at each time of the day there is always enough bagged cement to fulfil the costumer's orders. On the other hand, the warehouse's resources are limited, which means that there is a finite number of resources and these ones are only forklifts. These forklifts are also available at each time of the day. In addition, the warehouse has a limited number of docking bays and each docking bay is associated to a specific loading rate for each type of product available. This means that, for example, the docking bay 1 might have a bigger loading rate for the product 1 and a lesser one for the product 2, because the product 1 might be closer to the docking bay than the product 2. The loading rate is measured in number of pallets per minute.

To summarize all of the characteristics of the problem stated so far, the three-field notation $\alpha \mid \beta \mid \gamma$ of (Graham et al., 1979) is going to be adopted to describe the scheduling problem in study. The $\alpha$ field, given as $\alpha = \alpha_1\alpha_2\alpha_3$, for this problem in specific takes the value of $\alpha = 1$. For that to happen, the $\alpha_1 = \circ$, because the problem in study deals with a single machine environment. The $\alpha_2 = 1$ since there is only one machine, that is represented by the warehouse. And finally, the $\alpha_3 = \circ$ because there is not any stages on the process in study.

Regarding the $\beta$ field, which indicates job characteristics and is composed by seven different fields, for this case of study, only two of the seven fields exist, or are different from zero. These two fields are the $\beta_2$ and the $\beta_7$. Since each job is characterized by its release dates $\beta_2 = r_j$, and since the problem in study is considered as a serial batching problem $\beta_7 = s-batch$. Finally, the last field, that considers the optimality criterion that is going to be minimized, which is the makespan of the scheduling problem, appears like $\gamma = C_{\max}$. The final three-field notation for this problem is $1 \mid r_j, s-batch \mid C_{\max}$.

When looking in the literature for studies that could include the problem described in the last paragraph, it was not possible to find records of the exact same problem described so far. However, there are some records of researchers who have studied similar problems. Starting with the oldest record, in 1977, (Lenstra, Rinnooy Kan, & Brucker, 1977) were able to study several scheduling problems and actually proved they were strongly NP-hard. Among the scheduling problems studied by (Lenstra et al., 1977) the ones that are more similar to this study are the $1 \mid r_j, s-batch \mid \mathrm{L}_{\max}$ and the $1 \mid r_j, s-batch \mid \sum C_j$. Later in 1990 (Du & Leung, 1990) studied the problem of $1 \mid s-batch \mid \sum T_j$ where, at the time, they prove it to be NP-hard. In

1993, (Albers & Brucker, 1993) studied the problem of $1 \mid s-batch \mid \sum w_j C_j$ and they were able to prove it to be strongly NP-hard, at least at that time. Since these dates, to this day, these are the last records of problems identical to the one in study in this work. The thing that is missing in all of them is that none of it is trying to minimize the makespan, plus in some of the records the release dates did not exist. With these evidences it is possible to conclude that at the time, since no one has studied this problem in specific, there is no proof that this problem in study – $1 \mid r_j, s-batch \mid C_{\max}$ –, is in fact NP-hard or strongly NP-hard.

However, the purpose of this study is not to prove whether the problem is NP-hard or not. Instead, the goal is to create an algorithm capable of solving it to obtain optimal or, if not possible, at least, feasible solutions. If the problem in consideration is, in fact, NP-hard, then, what is going to happen is that it will run into computational difficulties at some point as the number of jobs increases (Azizoglu & Webster, 2001). If these computational difficulties start to happen, then the practical question that must be taken is, after all, what is the size of the problem – the number of jobs –, that allows it to be solve in a reasonable amount of time. Plus, in cases where the computational difficulties start to happen and the computational time to solve the problem increases, heuristics methods appear to be good solution to adopt. In this sense, in the next section the mathematical model is going to be presented and, after that, two heuristic methods are proposed to overcome the computational difficulties of the mathematical model.

## 4.4. MILP model

In this section a Mixed Integer Linear Programming (MILP) is proposed to optimize the problem of scheduling all batches such that the makespan is minimize. Before introducing the objective function and its restrictions, it is necessary to identify all the notation used, including the problem parameters and decision variables. In the next table the notation and its description is summarized.

*Table 1. Notation of the model parameters and decision variables*

| Notation | Description |
|---|---|
| **Model Parameters** | |
| $n$ | number of jobs |
| $m$ | number of docking bays – maximum length of a batch |
| $n_b$ | maximum number of batches possible |
| $n_p$ | number of products |
| $f$ | number of forklifts – minimum length of a batch |
| $j$ | index of the job, $j = 1, 2, \ldots, n$ |
| $i$ | index of the docking bay, $i = 1, 2, \ldots, m$ |
| $b$ | index of the batch, $b = 1, 2, \ldots, n_b$ |
| $p$ | index of the product, $p = 1, 2, \ldots, n_p$ |
| $J$ | set of jobs, $J = \{1, 2, \ldots, n\}$ |
| $M$ | set of docking bays, $M = \{1, 2, \ldots, m\}$ |
| $B$ | set of batches, $B = \{1, 2, \ldots, n_b\}$ |
| $P$ | set of products, $P = \{1, 2, \ldots, p\}$ |
| $t_j$ | type of material requested by job $j$ |
| $q_j$ | quantity of material requested by job $j$ |
| $r_j$ | release date of job $j$ |
| $l_{p,i}$ | loading rate of the product $p$ on the docking bay $i$ |
| **Decision Variables** | |
| $x_{j,b,i}$ | 1 if job $j$ belongs to batch $b$ and is loaded on docking bay $i$, 0 otherwise |
| $q_b$ | quantity of clients on batch $b$, $\geq 0$ |
| $p_b$ | processing time of batch $b$, $\geq 0$ |
| $a_b$ | availability of batch $b$, $\geq 0$ |
| $s_b$ | starting time of batch $b$, $\geq 0$ |
| $C_b$ | completion time of batch $b$, $\geq 0$ |
| $C_{\max}$ | makespan |

Giving this notation, the model is presented as follows:

*Minimize* $C_{\max}$ (1)

*Subject to:*

$$\sum_b \sum_i x_{j,b,i} = 1 \quad \text{for } j \text{ in } J \tag{2}$$

$$\sum_j x_{j,b,i} \leq 1 \quad \text{for } b \text{ in } B \text{ and } j \text{ in } J \tag{3}$$

$$f \leq q_b \leq m \quad \text{for } b \text{ in } B \tag{4}$$

$$p_b = \sum_j \sum_i \frac{q_j}{l_{t_j,i} \cdot f} \cdot x_{j,b,i} \quad \text{for } b \text{ in } B \tag{5}$$

$$a_b \geq r_j \cdot x_{j,b,i} \quad \text{for } j \text{ in } J,\ b \text{ in } B \text{ and } i \text{ in } I \tag{6}$$

$$s_b \geq a_b \quad \text{for } b \text{ in } B \tag{7}$$

$$c_b = s_b + p_b \quad \text{for } b \text{ in } B \tag{8}$$

$$s_b \geq C_{b-1} \quad \text{for } b \text{ in } B \text{ and } b > 1 \tag{9}$$

$$C_{\max} \geq C_b \quad \text{for } b \text{ in } B \tag{10}$$

The model is composed by one single objective function and nine constraints. The objective of this model, represented on (1), is to minimize the makespan. The makespan for this batch-processing machine is equal to the completion time of the latest batch processed. To guarantee that the makespan is the completion time of the latest batch is the function of the constraint (10). The minimization of the makespan usually allows minimizing the idle time of the warehouse's equipment (Oliveira, 2007).

The constraint (2) ensures that each job $j$ belongs to only one batch $b$ and has only one docking bay $i$ associated. Constraint (3) on the other hand, ensures that there is not more than one job on the same docking bay in the same batch. Constraint (4) is related with the length of each job that cannot be less than the number of forklifts and more than the number of docking bays. (5) is the constraint that allows to calculate the processing time of each one of the batches. The processing time of each batch is given by the sum of the quotients between the number of pallets each client, that belongs to the batch, ordered, and the multiplication of the loading rate associated to each client and the number of forklifts available. The constraint (6) ensures that the availability of the batch is given by the largest release time of the jobs that belong to the batch. This way the batch is only available to begin if all jobs are available. On the other hand, the constraint (7) ensures that the starting time of each batch must be the same or greater than the availability of the batch. (8) is the constraint that allows the calculation of the conclusion time of the batch, which is given by the starting time of the batch plus the processing time of it. And finally, (9) ensures that a certain batch $b$ can only start to be processed if the previous one has already concluded its process.

## 4.5. Heuristics

In this section, two different algorithms will be presented. These algorithms are heuristic procedures, also known as approximate algorithms. The goal now is not to cover all the solutions available and pick the best one, as the exact method does, but instead, to cover a limited area of the feasible region, or solution space, and find the best solution possible in that area. The first heuristics is a constructive algorithm, that starts with an empty initial solution and the second one is a local search algorithm that starts with the solution obtained with the constructive algorithm. In these two next sections these algorithms will be descripted and its results, as well as the results for the MILP model, will only be presented on the Chapter 5 – *Results and Discussion*.

### 4.5.1. Constructive Algorithm

For this first algorithm, the Constructive Algorithm (CA), the main goal is to achieve a first feasible solution. To do so, the first step of this algorithm is to order the list of jobs by the Earliest Release Date (ERD). Then, the jobs are grouped into batches until all jobs belong to a batch. The next table presents the general steps of the constructive algorithm.

*Table 2. Pseudo-code of the CA heuristic*

| **Algorithm 1** Constructive Heuristic Algorithm | |
|---|---|
| **Step 1** | Arrange jobs in order of the ERD |
| **Step 2** | While $j < n$: group the jobs in batches with the minimum length possible, in other words, where the length equals the number of forklifts available |
| **Step 2.1** | If the number of jobs remaining to group is less than the number of forklifts, then, add the remaining jobs to the last batch formed |
| **Step 3** | Assign docking bays to each job, for each batch |
| **Step 4** | Calculate the makespan of the final list of batches |

The Step 1 ensures that the first jobs that arrive to the warehouse are the first ones to be processed. To do so, on Step 2 the jobs are grouped in the minimum number possible aiming the minimization of the processing time of each batch. After grouping almost all jobs, if the remaining ones are not enough to create a new batch, in other words, in the number of remaining jobs is not the same as the number of resources – forklifts – available, then these jobs are added to the latest batch formed. If this situation happens, the last batch is going to be the batch with the greatest length. Only after the creation of the batches, will it be possible to calculate the makespan of the scheduling process and assign each one of the jobs to docking bays. The assignment of jobs to docking bays is made by a simple function that chooses, for each job, the docking bay that is still available in the batch and has the maximum loading rate possible considering the type of product requested. After this assignment, the formula to calculate the processing time for each batch is the same as the one already presented on the constraint (5). The final makespan is equal to the conclusion time of the last batch leaving the warehouse.

### 4.5.2. Metaheuristic Algorithm

The metaheuristic algorithm, on the contrary of the CA, instead of starting with an empty solution, starts with a base solution. With this base solution it is possible to achieve other solutions through small changes on the first one. These changes allow to create a neighborhood structure and, only there, it will be possible to look for a better solution than the first one. There are two characteristics that appear to be desirable when choosing a neighborhood. First, the neighborhood should provide what is called of "objective congruence," which is the same to say that solutions with good objective function values should be relatively near neighbors to other good solutions. The second desirable characteristic of a neighborhood is that it should allow for "diversity". If the search is too myopic, it may fail to locate good solutions which are located just beyond some relatively poor solutions, causing the search to get stuck at a poor local optimum. The characteristics of objective congruence and diversity therefore trade off against one another (Sampson & Weiss, 1993). While the congruence is going to be ensured by changes, or moves, in the solutions, that allow to maintain the search for best solutions, near to already good solutions. The diversity is going to be given by the Simulated Annealing (SA) approach, that is going to be used, that allows to accept bad solutions, with a certain probability, to not get stuck in local optimums. The neighborhood structure should allow to achieve the optimal solution.

SA is a metaheuristic widely used to solve difficult combinatorial optimization problems (Melouk, Damodaran, & Chang, 2004). SA is also a stochastic approach that endeavors to overcome local optimality by accepting bad solutions with a definite probability (Kadhim et al., 2018; Kadhim & Hanoon, 2018; Melouk et al., 2004). The basic idea is to create a path through the feasible region, from one solution to another, leading eventually to the optimum solution (Kadhim et al., 2018). The SA algorithm is an analog to the physical annealing of solids to attain minimum internal energy states (Kadhim et al., 2018). When generating the neighborhood structure, solutions are chosen from changes in the preceding solution by a probabilistic function of the improvement gained by the change. At the start, almost all changes are likely to be accepted, however, as the algorithm develops, the tolerance for bad solutions decreases, eventually to the point where only improvements are accepted (Kadhim et al., 2018; Melouk et al., 2004; Sel & Hamzadayi, 2018). The typical SA algorithm parameters are the initial temperature $T$, the cooling rate $r$ and the number of iterations for each temperature level $N$ (Dowsland & Thompson, 2012; Melouk et al., 2004; Sel & Hamzadayi, 2018).

The temperature, analogous to physical annealing, is a control parameter that is supposed to reduce at a fixed rate called cooling rate. If the final solution is to be independent of the starting point, then the initial temperature must be hot enough to allow free movement through the solution space (Dowsland & Thompson, 2012). For this problem it is expected to not have high values of temperature. Plus, the success of any SA is highly sensitive to the rate at which the temperature is reduced and, it is apparent from the theory that the temperature needs to be reduced slowly (Dowsland & Thompson, 2012). Empirical evidence from the literature shows that typical values for $r$ are in the range $0.8-0.99$ (Dowsland & Thompson, 2012; Melouk et al., 2004). The value of $N$ is often related to the size of the neighborhood and may vary from temperature to temperature. For low initial temperatures, for example, it is important to spend enough time looking for new solutions to ensure that the regions around a local optimum have been fully explored (Dowsland & Thompson, 2012). A random set of preliminary experimental runs helped to choose the values for these three parameters, being them $T=100$, $r=0.99$ and $N=100$. Besides these parameters, other important features are the moves to apply to current solutions to build the neighborhood structure.

Three moves were applied in this metaheuristic method to obtain the neighborhood structure. The first one, named Swap Length, choses the biggest batch, in other words, the batch with the biggest length, in terms of number of jobs in the batch, and randomly picks one of the jobs of that batch and places it on the previous or the next batch. If the biggest batch is the last one on the list, then the chosen job is placed on the previous batch. If the biggest batch is the first one, then the chosen job is placed on the next batch. This first move will allow to the local search algorithm to test which batch should be the one with the maximum length and, which job is the best to transfer from one batch to another. For instance, if in the initial solution, the biggest batch has three clients with high values of quantities ordered, and there is a subsequent batch that has the ones with the less quantities ordered, then, if this move is applied, it is likely that the makespan is decreased. It is a possibility because if the workload is better distributed, in other words, if the quantity of products to load is well distributed through the batches, it is expected to achieve better values of makespan.

The second move, named Swap Jobs, basically chooses two random batches, they only must be consecutive, and swaps two jobs. In other words, the job $j_1$, from the batch $b_1$, is placed in the batch $b_2$ and, the job $j_2$ is placed on the batch $b_1$. This second move has the same possible consequence of balance the workload of the batches, as the last one, and, plus, it also has the possible capacity of guarantee for the job $j_1$, for example, a biggest loading rate. Imagine that on the batch $b_1$ all jobs ordered the product $p_1$ and there are only two docking bays with the maximum loading rate, let us say it is one pallet per minute. This means that if the job $j_1$ is transferred to the batch $b_2$ where there are not any jobs requesting the product $p_1$, and another job from $b_2$ is transferred to the batch $b_1$, then, it is possible that the makespan is decreased.

Finally, the third and last move, named Spread Jobs, basically choses a random batch and splits it in a random position and spreads one part to one subsequent batch and the other one to another subsequent batch. This move is only applied if the final length of each one of the batches that are going to gain more jobs, is not bigger than the number of docking bays available. This third move allows the local search algorithm to decrease the total number of batches, and, in some conditions, it can be advantageous. With these three moves and initial parameters defined, a SA approach was created as a local search method to improve a given base solution. In the next table the pseudo-code for the local search algorithm is presented.

*Table 3. Pseudo-code of the metaheuristic algorithm based on a SA approach*

| **Algorithm 2** Metaheuristic Algorithm – SA approach | |
|---|---|
| **Step 1** | Set $T=100$; $r=0.99$; $N=100$ |
| **Step 2** | Get initial solution from the constructive algorithm |
| **Step 2.1** | Determine the objective, $C_{\max}$, for the initial solution. Let current solution $C_{\max}=initialsolution$ |
| **Step 3** | Set n=0; |
| **Step 4** | Generate neighboring solution: set $move=\text{Uniform}[1,3]$; if $move=1$: Swap Length on current solution; else if $move=2$: Swap Jobs on current solution; else if $move=3$: Spread Jobs on current solution |
| **Step 5** | Calculate the objective of the neighboring solution ($C'_{\max}$) |
| **Step 6** | Save $C'_{\max}$ and neighboring solution |
| **Step 7** | If $C'_{\max}<C_{\max}$, current solution=neighboring solution and $C_{\max}=C'_{\max}$. Else if $\text{Uniform}[0,1]<\exp\{(C_{\max}-C'_{\max})/T\}$, current solution=neighboring solution. |
| **Step 8** | $n=n+1$; repeat steps 3-7 until $n=N$ |
| **Step 9** | $T'=T\cdot r$; $T=T'$ |
| **Step 10** | Repeat steps 3-9 until $T=1$ |
| **Step 11** | Return best value of $C_{\max}$ found |

On the Step 1 the three main parameters of the model are defined. These parameters, associated to a typical SA model, define the initial state of the process of local search and are the ones that decide how the heuristic process occurs as well as how it stops. On Step 2 and 2.1 the initial solution is defined as well as the initial objective value, $C_{\max}$. On Step 3 a new cycle is defined, this one is going to be repeated for each value of temperature, until $n=N$, as it is shown on Step 8. In this cycle is the generation of neighboring solutions. Therefore, on Step 4 is the choice of the move to be applied on the current solution, on Step 5 is the calculation of the new objective value, $C'_{\max}$ and on Step 6 this value, as well as the solution, are saved. On Step 7 is the process of acceptance of the new solution. The solution is accepted if it is better than the previous one or, if it is not better than the previous one, it is accepted by a certain probability function. This probability function, which comes from the SA approach, is presented in the next equation (11).

$$u < e^{\frac{C_{\max}-C'_{\max}}{T}} \qquad (11)$$

In (11), $u$ is a random number generated in the interval $[0,1]$, and it defines if the solution is accepted or not. If $u$ is minor than the criteria defined in (11), then the solution, despite having a worst objective value than the previous one, is accepted. This is, in fact, the technique used by SA to accept worst solutions to escape local optimums. On Step 8 the number of iterations is updated and only when leaving the cycle of iterations, will the temperature be updated, on Step 9. Step 10 defines the stop criterion, which is when the temperature is set to 1. Finally, on Step 11, the best solution found on the local search is returned. This is an additional step, considering the typical SA algorithm, and it is important because it returns the best solution found in all of the search process. Without this step, what would happen is that, as the SA allows worst solutions under a certain probability, the last solution found by this approach, could not be the best found in all process. That is why on Step 6 all solutions are saved and on Step 11 only the best solution found is presented, instead of the last one found.

Giving these three developed methods for solving the problem, in the next section it will be shown how they were tested and implemented. It will be followed by a results analysis as well as a discussion. The goal of this work is to solve the problem and present feasible, and when possible, optimal solutions.

# 5. Computational Experiments

In this chapter the three different methods presented previously, the MILP model, the CA and the SA algorithms are going to be tested. It is usual, and valuable, to include computational tests of the proposed algorithms, and these tests aim to, for example, demonstrate the potential of new algorithms in specific situations, demonstrate that an algorithm is practical, identify conditions under which an algorithm performs best or worst, and compare competing algorithms (Hall & Posner, 2001).

To perform the tests, it was necessary to generate data that could allow a good evaluation and comparison of the three methods. Besides generating the data, to perform the tests, it was necessary to implement the procedures. The MILP model was implemented using the AMPL language and submitted in the NEOS Server and solved through the *Gurobi* solver. The heuristic models were implemented in *Java* language and run on a PC with the following characteristics: *Intel Core* i3-2365M with 1.40GHz and 4GB of RAM, in the operating system *Windows 10*. The data description and respective computational results are presented in the next sections.

## 5.1. Instance Sets

Due to the lack of benchmark instances in the literature, the performance of the exact and heuristic methods is going to be evaluated by solving randomly generated instances. These instances are going to be generated based on previous work present in literature to have a variety set of instances with different conditions and workloads. Some characteristics of the instances generated, that are considered to be important for the computational evaluation (Hall & Posner, 2001), are, for example, the variety, the practical relevance, and the regularity. On one hand, the variety is obtained through generating different sizes of instances. On the other hand, the practical relevance and the regularity ensure that the data generated is similar to real-world scenarios and that each instance is treated in a similar way, respectively.

The number of cement companies in study – each company defines a set of instances –, is three. These three companies differ on the machine environment, or in other words, in the length of the warehouse. In the Table 4 it is possible to see the main parameters of each company.

*Table 4. Companies' characteristics*

| Company | No. of Docking Bays | No. of Forklifts | No. of products Available |
|---|---|---|---|
| **1** | 6 | 2 | 3 |
| **2** | 12 | 3 | 3 |
| **3** | 16 | 3 | 4 |

For more details on the loading rates for each product, at each docking bay, of the companies' warehouses, check Appendix I. For each company, or set, several instances were generated varying the job's parameters. The job's parameters include the number of jobs $n$, the type of product requested for each job $t_j$, the quantity of material requested $q_j$ and the releases dates of each job $r_j$. They were randomly generated and can cover different circumstances.

The number of jobs per set that will be considered are $n = 10,\ 20,\ 50,\ 100,\ 200$. These values assure that the experiment will be done starting with small size problems to reasonable large size ones. Each job parameter followed a different distribution, the type of product, $t_j$, uses a discrete distribution, presented in the Table 5 for each company. With this distribution it is possible to distinguish the two most demanded products from the other(s). This way, the practical relevance is ensured, since in every warehouse of every cement company in study, there are products more requested than others.

*Table 5. Discrete distribution of the demand for each type of product*

| | $t_j$ | % of the demand |
|---|---|---|
| **Company 1** | 1 | 37,5% |
| | 2 | 37,5% |
| | 3 | 25,0% |
| **Company 2** | 1 | 37,5% |
| | 2 | 37,5% |
| | 3 | 25,0% |
| **Company 3** | 1 | 30,0% |
| | 2 | 30,0% |
| | 3 | 25,0% |
| | 4 | 15,0% |

The quantity of material requested, $q_j$ uses a normal distribution: $q_j \sim N(\mu = 6, \sigma = 2)$. For the release dates, on the other hand, $r_j$ uses a uniform distribution: $r_j \sim U[0, \tau R_{\max}]$. Where, the $R_{\max}$ measures the expected total processing time. It is calculated as the following equation (12) suggests. $q_{avg}$ is the average amount of product requested, $v_{avg}$ is the average loading rate considering all the docking bays and respective loading rates for each type of product, $n$ is the total number of jobs and $m_{avg}$ is the average length of batches given as the average between the number of docking bays and the number of forklifts.

$$\frac{q_{avg}}{v_{avg}} \cdot \frac{n}{m_{avg}} \tag{12}$$

Finally, the $\tau$ element on the uniform distribution of $r_j$ is given as $\tau \in \{0.5, 0.75, 1, 1.25, 1.5\}$ and it is based on the work of authors such as (Chu, 1992; Kooli & Serairi, 2014; Selim Akturk & Ozdemir, 2000), and it guarantees the spread of the release dates of the jobs. As the size of $\tau$ gets larger, the release dates are more spread out. The goal is to analyze how the algorithms behave in all kind of circumstances, including the times when the clients arrive to the facilities closer or more distant from each other. The Table 6 gives a summary of all the parameters of the problem already described as well as the number of alternatives of each parameter for each instance, and the total number of instances generated.

*Table 6. The parameters of the problem*

| **Parameter** | **Alternatives** | **Values** |
|---|---|---|
| $n$ | 5 | 10, 20, 50, 100, 200 |
| $t_j$ | 1 | Presented in Table 5 |
| $q_j$ | 1 | $\sim N(6,2)$ |
| $r_j$ | 5 | $\sim U[0, \tau R_{\max}]$, $\tau \in \{0.5, 0.75, 1, 1.25, 1.5\}$ |
| **No. of Companies** | 3 | |
| **Total no. of instances** | 75 | |

## 5.2. Results and Discussion

Each one of the 75 instances generated in the last section was submitted to each one of the algorithms: the MILP, CA and SA. For the SA algorithm, each instance was run six times, since the SA algorithm is made by some probabilistic functions. The probability functions give the algorithm some uncertainty and that is why it is usual to run it more than one time to see what range of solutions it is capable to obtain. In this section all results will be presented as well as a discussion of what they represent. In the Appendix II. the results are presented in tables with the computational results for each value of $n$.

To start the analysis of the results, the following Gantt diagrams pretend to give a visual example of how the solutions change according to the algorithm used. The example presented refers to the

Company 1, for $n=10$ and $\tau=1,5$ which is a solution where the CA could not reach the MILP solution, but the SA did. In the Figure 6, Figure 7 and Figure 8 three different solutions are presented, the Figure 6 is the one obtained through the CA, the Figure 7 is the worst solution obtained with the SA algorithm and, finally, the Figure 8 is the one obtained with the MILP that is equivalent to the best solution found by the SA.

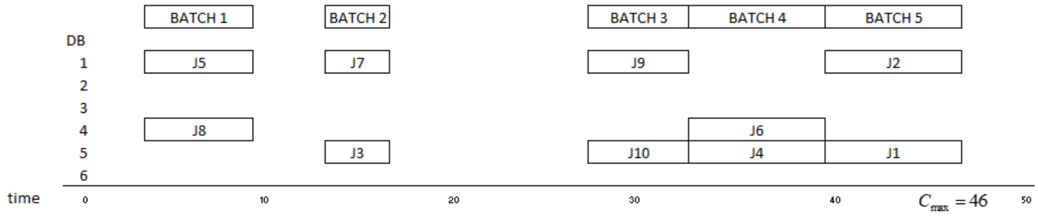


*Figure 6. Gantt diagram solution for the instance: Company 1, n=10 and* $\tau=1.5$ *using the CA.*

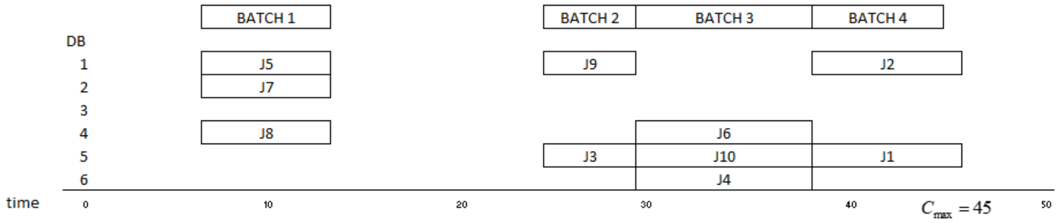


*Figure 7. Gantt diagram solution for the instance: Company 1, n=10 and* $\tau=1.5$ *using the SA.*

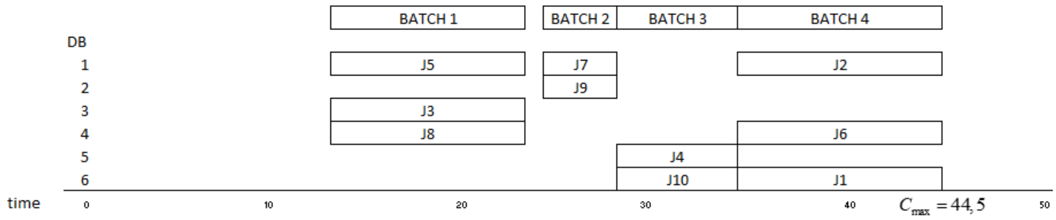


*Figure 8. Gantt diagram solution for the instance: Company 1, n=10 and* $\tau=1.5$ *using the MILP.*

As it is possible to see from Figures 6, 7 and 8, as the solution evolves from CA to MILP model, the objective function improves – the makespan goes from 46 minutes to 44,5 minutes – and achieves a point where the work is concentrated in one region only. This is favorable mainly for the warehouse's resources since it appears to improve the workflow. In fact, with the schedule obtained using the MILP model – the optimum solution – the forklifts can do the work all at once, since the batches enter the warehouse almost one after another. The schedule of the SA algorithm solution is better than the schedule of the CA, even it being the worst solution found by SA. The best solution found by the SA algorithm is equal to the optimum solution provided by the MILP model and presented in Figure 8. As it is possible to see the SA method has the capacity to improve the CA solution and, in this case as it happened in other instances, the SA algorithm could really achieve the optimum solution. The graphics of the Figures 9 to 13 include the deviation from the MILP model solutions for the CA and SA models. Through the Figure 9 to Figure 13 it is also possible to see in how many instances the SA algorithm could improve the CA solutions. For the case of the SA solutions, it is the deviation between the best solution reached by the SA algorithm and the solution achieved by the MILP model.

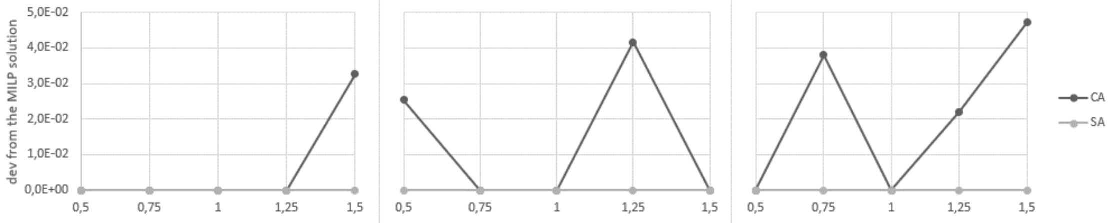


*Figure 9. Deviation from the optimal for n=10 for each instance, starting with the Company 1 to Company 3, with increasing values of $\tau$ , for each company.*

Figure 9 presents the results for $n=10$. As it is possible to see, for the instances where the CA did not reach the optimum value, $dev \neq 0$, the SA algorithm, in all situations, could achieve, at least one time, the solution reached by the MILP model, which for these instances is the optimum.

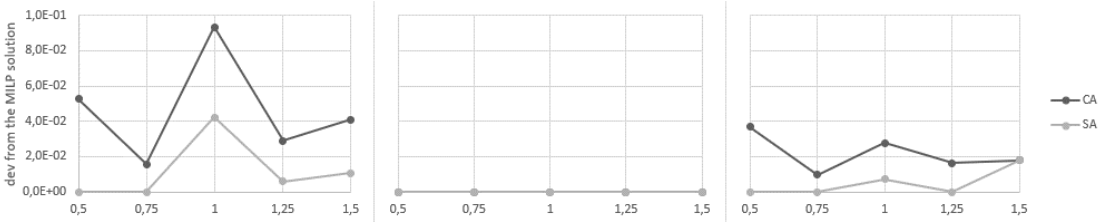


*Figure 10. Deviation from the optimal for n=20 for each instance, starting with the Company 1 to Company 3, with increasing values of $\tau$ , for each company.*

On the graph of Figure 10, that presents the results for $n=20$, the SA method could not reach the optimum value in all instances. There were five instances where the SA method did not achieve the optimum value. However, the SA model could reach, at least one time in almost every instance, solutions closer to the optimum value comparing with the solutions of the CA solutions. In other words, the SA algorithm, in the instances where it failed to reach the optimum values, at least it could improve the solutions first obtained with the CA. The only instance where this did not happen was in the last instance which corresponds to the instance of the Company 3 and $\tau=1,5$.

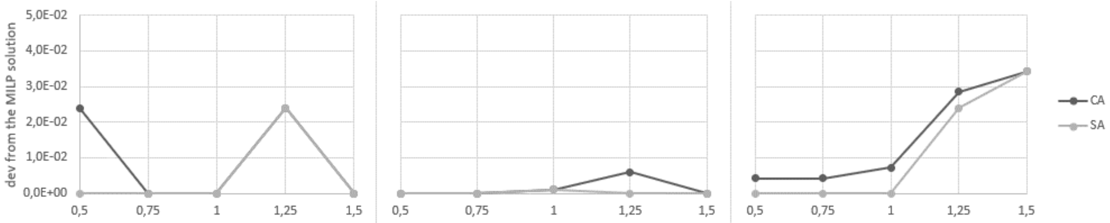


*Figure 11. Deviation from the optimal for n=50 for each instance, starting with the Company 1 to Company 3, with increasing values of $\tau$ , for each company.*

In the Figure 11, that presents the results for $n=50$, there are instances where both CA and SA reached the optimum values, there are other instances where the CA did not reach the optimum but the SA did, there are other instances where neither the CA or SA reached the optimum but the SA managed to improve the CA results and, finally there are instances where neither the CA or the SA reached the optimum and the SA also did not manage to improve the CA solution. For these three first graphics, besides the situations of improving or not improving CA solutions, or reaching or not reaching the optimum, the values of the deviation are all $\geq 0$ but still close to zero. This proves that the solutions, even if they are not the optimum solutions, they are near to the optimum which is a good signal about the efficiency of the algorithms.

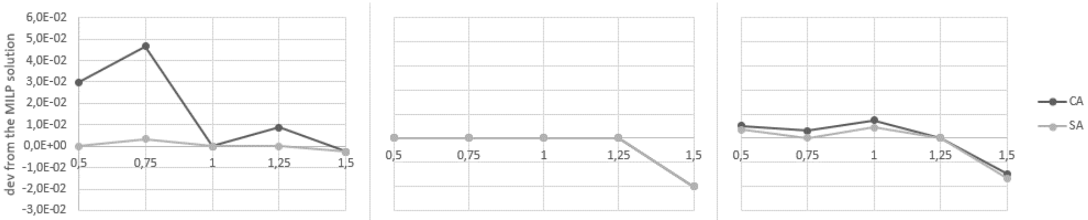


*Figure 12. Deviation from the optimal for n=100 for each instance, starting with the Company 1 to Company 3, with increasing values of $\tau$ , for each company.*

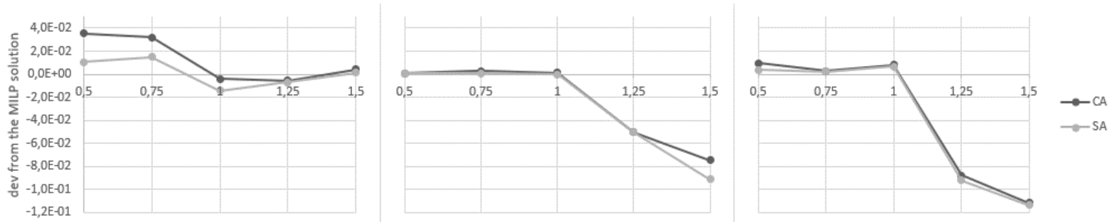


*Figure 13. Deviation from the optimal for n=200 for each instance, starting with the Company 1 to Company 3, with increasing values of $\tau$ , for each company.*

For the two last graphs of Figures 12 and 13, there are instances where the deviation from the MILP solution becomes $<0$. Since the maximum computational time dispensed by the NEOS server is 8 hours and, if by that time the MILP model did not has the time to test all possibilities, what happens is that it returns a solution with no guarantees of optimality. In this sense, for some larger instances the MILP model could not get to the optimum solution, or at least there are no guarantees that the solution achieved is optimum, since it ran out of time. From the results, presented in the Appendix II., it is possible to verify that this type of situation happened for $n=50$ to the company 3 when $\tau=1,5$; for $n=100$ to the company 1 when $\tau=1,25$ and $\tau=1,5$, to company 2 when $\tau=1,5$ and to company 3 when $\tau=1,25$ and $\tau=1,5$; and for $n=200$ to the company 1 when $\tau=1$, $\tau=1,25$ and $\tau=1,5$, to company 2 when $\tau=1$, $\tau=1,25$ and $\tau=1,5$, and finally, to company 3 when $\tau=1,25$ and $\tau=1,5$. From here it is possible to see that for larger instances, $n > 50$ and larger values of $\tau$, the MILP model starts having computational difficulties in finding the optimum solution, which is a signal of the problem difficulty. For the case where the number of jobs increases, i.e., when the length of the instances gets bigger, it was already expected that the problem started having computational difficulties. In fact, as the instances get bigger, there are more combinations for the solver to compute and, at some point, it cannot compute all the possibilities in a reasonable amount of time and the problem becomes computationally difficult. This also gives some hints of the problem NP-hardness. On the other hand, for the $\tau$ values, it was also expected for the instances to became hard to solve as the values of $\tau$ grow since the problem is relatively simple when $\tau$ is small, because the release dates are not scattered (Selim Akturk & Ozdemir, 2000). In fact, when $\tau$ is small, the problem rapidly becomes a problem without release dates after having scheduled a few jobs, which is an easier class of problems (Chu, 1992). Having these computational difficulties in consideration, it is now possible to understand why there are cases where the deviation assumes a negative value ($< 0$). These cases, that start to happen for instances where $n = 100$ and $n = 200$, as it is possible to see on Figure 12 and Figure 13, occurred in instances where the MILP model could not get to the optimum value and, both the CA and SA models achieved better values of makespan than the MILP. This also proves the efficiency of the heuristic algorithms that, in shorter periods of time, can achieve best solutions, for larger instances. In the Figure 14 and Figure 15 it is possible to see how shorter, in average, these periods of time really are. The Figure 14 present a bar chart with the average computational time for each method, in each company. The Figure 15 presents a bar chart with the average computational time for each method, for each $\tau$ value. Note that for the CA, comparing with the two other methods, the computational time needed to solve the problem is so smaller that it is not possible to see the bar that corresponds to this method.

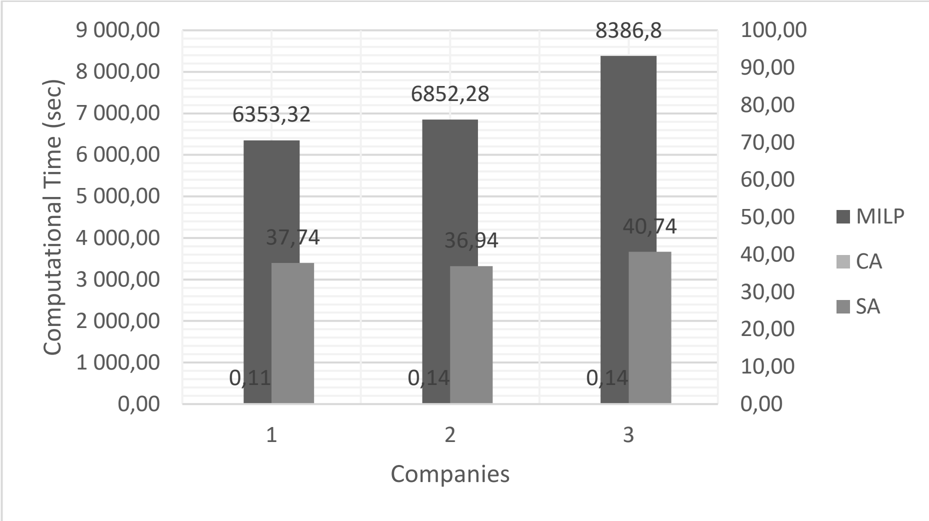


*Figure 14. Average computational time for each method, for each company.*

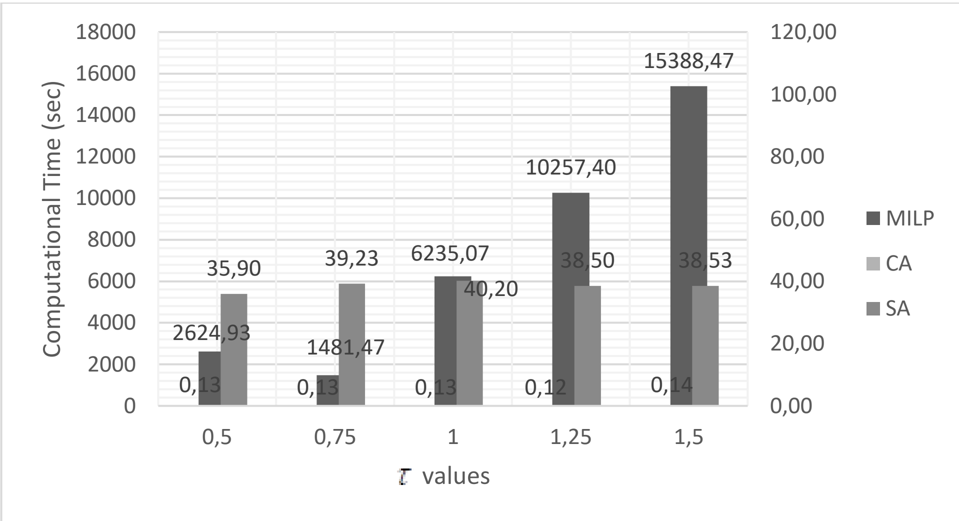


*Figure 15. Average computational time for each algorithm, for each value of $\tau$ .*

From Figure 14 and Figure 15 it is possible to confirm that when both instances get bigger and release dates get spreader, the computational effort of the problem gets harder for the MILP model. For the heuristic models, no matter the size of the instance or the level of spread of the release dates, the computational time needed to solve the problem is, in average, always shorter than the exact method approach. Despite the average computational difficulties of the MILP model, considering the heuristic methods, there are some instances that it could reach the optimum solution in a reasonable amount of time. In the Figure 16, Figure 17 and Figure 18, the evolution of the computational time for each model, both exact and heuristics, in each company, for each instance size, is presented.

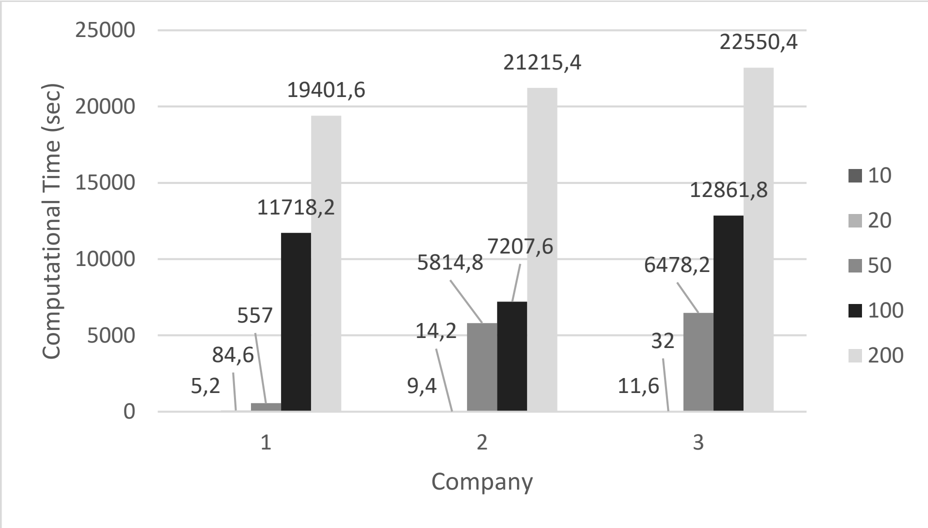


*Figure 16. Evolution of the computational times per company for each n, for the MILP model.*

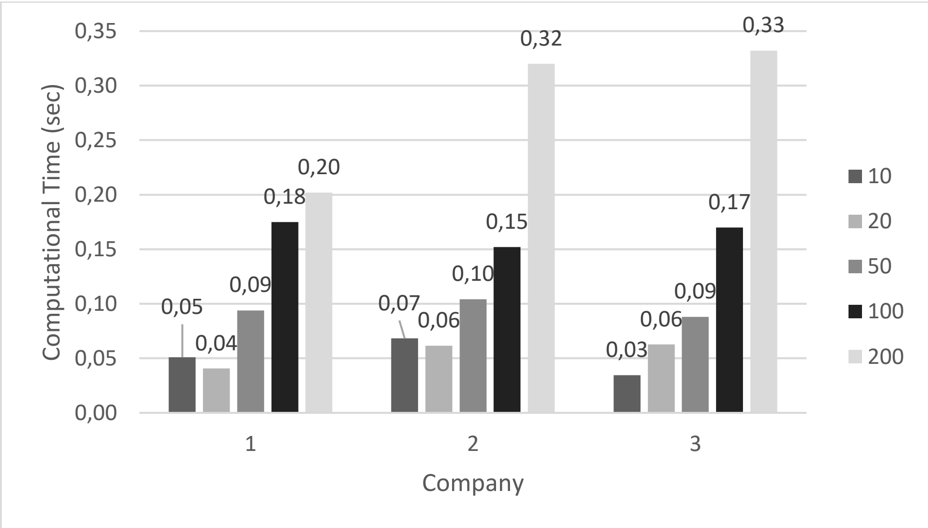


*Figure 17. Evolution of the computational times per company for each n, for the CA.*

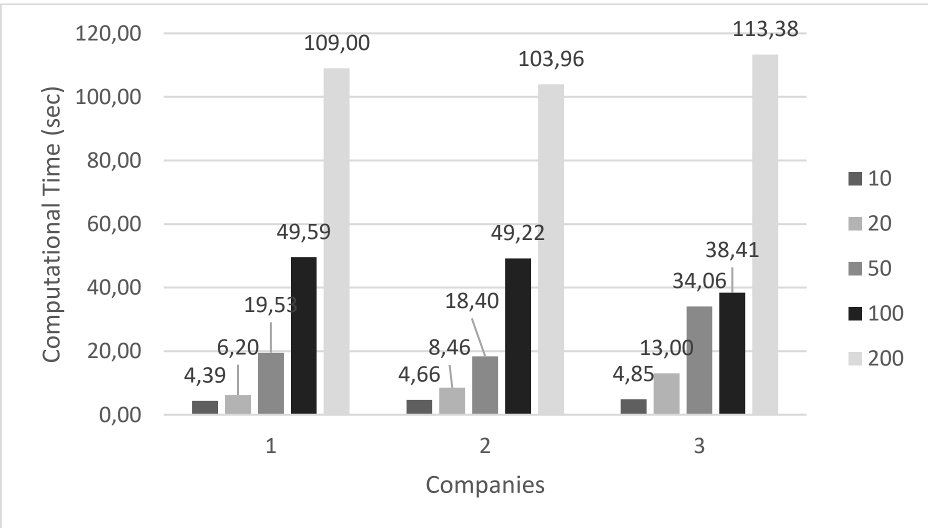


*Figure 18. Evolution of the computational times per company for each n, for the SA algorithm.*

For the three methods implemented, when the number of jobs increases, so does the computational time, as expected. For the MILP approach, it is clear why the computational time increases, since this problem is characterized by being a combinatorial problem, and it was something predictable already in the previous chapter of this work. For the heuristic models, the computational time also increases since the steps that each one of the algorithms must follow, as the number of jobs increases will take longer to compute. However, while the maximum average computational time reached for the MILP model was almost 8 hours – without guarantees of optimality –, for the CA it was 0,33 seconds and for the SA approach it was 114 seconds. With these results of the differences of computational times for each algorithm and having in consideration the previous study about the average deviation from the optimum for the heuristic models, it is safe to say that solutions found by the heuristic models are of good quality and they can give solutions near the optimum or even the optimum. To conclude, a final analysis was made about the influence of the warehouses' features in the achievement of good solutions comparatively to the optimum. In the Figure 19 it is presented the percentages of cases where solutions provided by the heuristic models were the same, best or worse than the ones provided by the MILP model. Again, the solutions reach by the heuristic models are only better than the MILP when this last one did not reach the optimality due to having reached the maximum computational time available by NEOS server.

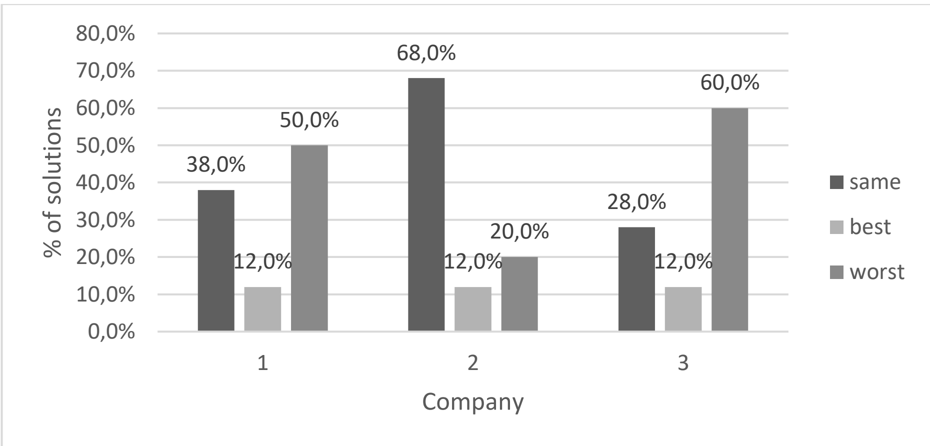


*Figure 19. Percentage of solutions reached by the heuristic algorithms that are the same, best or worse than the ones provided by the MILP model.*

For each company, 12% of the solutions found by the heuristic methods are better than the ones reached by the MILP model. A possible explanation for this same percentage for each company might be the fact that for each company, the MILP model had difficulties in the same values of $n$, in this case, for the largest values of $n$. Plus, it is possible to verify a large difference between the percentage of worst cases between the company 2 and the two others. This suggests that there is something in the company 2 that eases the process of achieving the optimum solutions, since the percentage of better solution is the same for the three companies. From company 1 to 2, what changes is the amount of docking bays available and the number of forklifts, which consequently increases the number of alternatives where jobs could be assigned and the number of resources to do the work. On the other hand, from company 2 to 3, what changes is also the number of docking bays and the number of materials available. Looking to the Figure 19 it seems possible to assume that the company 2 has the most favorable conditions to allow the algorithms to reach best values of the objective function, comparatively to the two other companies.

# 6. Conclusion

This dissertation presented a case study in the cement industry. Inserted in a project called UH4SP, the goal of this dissertation was to study the operation of loading trucks in a warehouse, related with the cement industry. Despite the link with the cement industry, this work aims to be a contribution to other industries, since the operation of loading trucks in warehouses is a common logistic process in several industries.

The literature review provided in this work proved the importance of the logistics and SCM in the achievement of improvements for companies. These improvements usually come as competitive advantages that companies can reach through the monitorization and the optimization of their supply chains. Among the supply chain's activities is the distribution. The distribution, as the operation of delivering the final product or service to the final client, is given as an important and critical activity. On one hand, the importance is given by the fact that the distribution has the task to control whether the product or service reaches the final client in the right conditions and at the right time. On the other hand, the critical characteristic is given by the fact that, if any mistake or delay happens in the process of distribution, it can directly affect the final client, lowering the service levels as well as the company reputation. The distribution itself is an activity that includes other minor activities. Among others there is the warehousing activity. The warehousing is given as an important activity to quickly answer variations in demand. To satisfy the clients' orders in the fastest time possible, having finished products available in stock becomes an imperative feature. The warehousing activity must be efficient otherwise there will be unnecessary costs in stake. For instances, if the stock level becomes higher than what is necessary, the company will incur in avoidable costs. In order to achieve higher efficiency levels, decision-making activities related with both the design and operations in the warehouse, must be optimized. Inside the warehouse operations there is the shipping activity characterized by being the operation responsible for making the product leave the warehouse. The shipping activity is in return characterized by decision-making processes such as the scheduling and assignment of trucks – that usually are the means of transport of the products – to docking bays. With the literature review made about all these topics addressed so far – the distribution, the warehousing and the shipping – it was possible to give a general framework of the real problem inside of what it is the scope of the logistics and SCM. In addition, the topics of scheduling and the methodologies to solve scheduling problems were also addressed in the literature review. The research about these topics provided a powerful tool to both characterize and solve the real problem in study. One advantage of studying the literature, is that it is possible to compare the already studied problems with problems that are still about to solve, and with that comparison make conclusions about how to formalize and solve problems. Basically, this was the main goal of studying the scheduling field. Only after understanding how scheduling problems are defined and characterized, it was possible to characterize the real problem of this dissertation. Plus, only with the right knowledge of how scheduling problems are solved, it was possible to design the needed models to solve the real problem. Concluding, the literature review made in this dissertation proved to be a great source of knowledge needed to frame, characterize, formalize and solve the real problem.

Considering the knowledge acquired with the literature review, it was possible to study the real problem as an analogy to the machine scheduling problem. But, after solving the problem, a detailed characterization of it was necessary. First, and to better understand what type of industry the cement industry is, a brief research about the state of this industry was addressed. With this research it was possible to conclude that the cement industry is a growing industry and its growth is directly linked to the globalization and the population growth. Being a growing industry involves higher levels of efficiency to better meet the demand requirements. In what concerns the state of the art of the shipping activity in the cement industry, it was not possible to find many studies about the matter. This fact makes possible to conclude that this work addresses some contributions to the shipping process in the cement industry, more precisely, to the process of scheduling and assigning trucks to the warehouse's docking bays. Plus, since no background was found and to help the process of formalizing the problem, some assumptions were needed to simplify the problem. The simplification of the problem is needed to later formalize it. After the formalization, the problem was treated as a serial batch processing machine scheduling problem. To solve the problem, an exact method, more specifically a MILP model, was developed. However, since this method showed computational difficulties for larger instances and to overcome these difficulties, two heuristics were further developed. The first one was created aiming to achieve a first feasible solution. The second one was developed aiming to improve the solution obtained with the first heuristic algorithm. Hence, the first heuristic is given as a Constructive Algorithm (CA), and the second one as a metaheuristic method. The results obtained through computational tests showed that for the instances where the MILP model was able to reach the optimum, both heuristics presented solutions of good quality, some of them even reach the optimum. Plus, the average computational time is larger for the MILP model (in the range of 1000 seconds), following the metaheuristic (in the range of 114 seconds) and last the fast algorithm the CA (in the range of 0,3 seconds). For the cases where the MILP model could not reach the optimum solutions, due to maximum computational time limits to process – being the limit 8 hours –, the heuristic algorithms managed to achieve better solutions in less than one second for the CA, and less than one minute for the metaheuristic method.

Regarding the future work proposals, first, a possible suggestion could be to try to create other constructive algorithms, as well as other metaheuristics approaches, to compare with the ones already developed in this work. With other methods it would be possible to understand the limitations and/or advantages of the algorithms presented in this dissertation. Another idea would be to test other moves in the metaheuristic. As the moves applied in metaheuristic approaches are, usually, directly related to the solutions' quality, to test other moves rather than the ones implemented could provide another vision and would help to understand which moves are better. Another challenge would be to transform the main problem in a shop scheduling problem since, in some industries, it is possible for clients to require more than one type of product. If the clients demand is more than one type of product, in analogy to the machine scheduling, is the same as having a job with more than one operation. In other words, it is the same as having more than one stage in the process. The problem in study in this dissertation would then be turned into a shop scheduling problem and it could give origin to an all-new study.

To conclude, even if this work remains as a study framework for future implementations in the real life, it showed up to be an innovative work and of high scientific value. Since, according to the current literature studied, the number of studies regarding the scheduling of trucks to warehouses, not including cross-docking warehouses, is a small number, this work proved to be a contribution for future researches in the field. Therefore, to finish this dissertation and as an inspiring thought for future researches that are trying to solve, or at least proposing ways to solve, problems, just remember that, as Gaston Bachelard said, and citing: "*The characteristic of scientific progress is our knowing that we did not know*", because only knowing that we do not know, we will be able to discover and learn. There is no learning without the unknowing.

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# Appendix

## Appendix I.

*Table 7. Loading Rates for each product, at each docking bay, in pallets per minute, for Company 1*

| **Product** | **WAREHOUSE CONFIGURATION** | | | | | |
|---|---|---|---|---|---|---|
| **1** | 1,0 | 1,0 | 0,8 | 0,5 | 0,2 | 0,2 |
| **2** | 0,2 | 0,2 | 0,5 | 0,8 | 1 | 1 |
| **3** | 0,2 | 0,2 | 0,5 | 1 | 0,5 | 0,2 |
| | DB1 | DB2 | DB3 | DB4 | DB5 | DB6 |

*Table 8. Loading rates for each product, at each docking bay, in pallets per minute, for Company 2*

| **Product** | **WAREHOUSE CONFIGURATION** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 1,0 | 1,0 | 0,8 | 0,5 | 0,5 | 0,2 | 0,2 | 0,5 | 0,5 | 0,8 | 1 | 1 |
| **2** | 0,5 | 0,8 | 1 | 1 | 0,8 | 0,5 | 0,5 | 0,8 | 1 | 1 | 0,8 | 0,5 |
| **3** | 0,2 | 0,2 | 0,2 | 0,5 | 0,8 | 1 | 1 | 0,8 | 0,5 | 0,2 | 0,2 | 0,2 |
| | DB1 | DB2 | DB3 | DB4 | DB5 | DB6 | DB7 | DB8 | DB9 | DB10 | DB11 | DB12 |

*Table 9. Loading rates for each product, at each docking bay, in pallets per minute, for Company 3*

| **Product** | **WAREHOUSE CONFIGURATION** | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 1 | 1 | 0,8 | 0,8 | 0,5 | 0,5 | 0,2 | 0,2 | 0,1 | 0,1 | 0,1 | 0,1 | 0,1 | 0,1 | 0,1 | 0,1 |
| **2** | 0,5 | 0,5 | 0,8 | 0,8 | 1,0 | 1,0 | 0,8 | 0,8 | 0,5 | 0,5 | 0,2 | 0,2 | 0,1 | 0,1 | 0,1 | 0,1 |
| **3** | 0,1 | 0,1 | 0,1 | 0,1 | 0,2 | 0,2 | 0,5 | 0,5 | 0,8 | 0,8 | 1 | 1 | 0,8 | 0,8 | 0,5 | 0,5 |
| **4** | 0,1 | 0,1 | 0,1 | 0,1 | 0,1 | 0,1 | 0,1 | 0,1 | 0,2 | 0,2 | 0,5 | 0,5 | 0,8 | 0,8 | 1 | 1 |
| | DB1 | DB2 | DB3 | DB4 | DB5 | DB6 | DB7 | DB8 | DB9 | DB10 | DB11 | DB12 | BD13 | DB14 | DB15 | DB16 |

# Appendix II.

*Table 10, Computational results for n=10*

| Company | $\tau$ | MILP | | | CA | | | | SA | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $C_{\max}$ | CT (sec) | No. Batch | $C_{\max}$ | CT (sec) | No. Batch | Dev | Best $C_{\max}$ | Avg $C_{\max}$ | Worst $C_{\max}$ | Avg CT (sec) | Avg No. Batch | Dev |
| 1 | 0,5 | 28,5 | 6,00 | 5 | 28,5 | 0,08 | 5 | 0,0E+00 | 28,5 | 28,5 | 28,5 | 4,40 | 5 | 0,0E+00 |
| | 0,75 | 28,5 | 5,00 | 5 | 28,5 | 0,07 | 5 | 0,0E+00 | 28,5 | 28,5 | 28,5 | 4,32 | 5 | 0,0E+00 |
| | 1 | 32,5 | 5,00 | 5 | 32,5 | 0,04 | 5 | 0,0E+00 | 32,5 | 32,5 | 32,5 | 4,12 | 5 | 0,0E+00 |
| | 1,25 | 36,5 | 5,00 | 5 | 36,5 | 0,04 | 5 | 0,0E+00 | 36,5 | 36,5 | 36,5 | 4,91 | 5 | 0,0E+00 |
| | 1,5 | 44,5 | 5,00 | 4 | 46 | 0,03 | 5 | 3,3E-02 | 44,5 | 44,8 | 45 | 4,20 | 4 | 7,4E-03 |
| 2 | 0,5 | 23 | 11,00 | 3 | 23,6 | 0,09 | 3 | 2,5E-02 | 23 | 23 | 23 | 4,85 | 3 | 0,0E+00 |
| | 0,75 | 22 | 10,00 | 3 | 22 | 0,04 | 3 | 0,0E+00 | 22 | 22 | 22 | 4,71 | 3 | 0,0E+00 |
| | 1 | 22 | 5,00 | 3 | 22 | 0,05 | 3 | 0,0E+00 | 22 | 22 | 22 | 4,40 | 3 | 0,0E+00 |
| | 1,25 | 23 | 16,00 | 3 | 24 | 0,13 | 3 | 4,2E-02 | 23 | 23 | 23 | 4,73 | 3 | 0,0E+00 |
| | 1,5 | 27,7 | 5,00 | 3 | 27,7 | 0,04 | 3 | 0,0E+00 | 27,7 | 27,7 | 27,7 | 4,61 | 3 | 0,0E+00 |
| 3 | 0,5 | 23,3 | 6,00 | 3 | 23,3 | 0,03 | 3 | 0,0E+00 | 23,3 | 23,3 | 23,3 | 4,54 | 3 | 0,0E+00 |
| | 0,75 | 25,3 | 6,00 | 3 | 26,3 | 0,03 | 3 | 3,8E-02 | 25,3 | 25,3 | 25,3 | 4,92 | 3 | 0,0E+00 |
| | 1 | 28,3 | 10,00 | 3 | 28,3 | 0,03 | 3 | 0,0E+00 | 28,3 | 28,3 | 28,3 | 5,04 | 3 | 0,0E+00 |
| | 1,25 | 31 | 26,00 | 3 | 31,7 | 0,05 | 3 | 2,2E-02 | 31 | 31 | 31 | 5,06 | 3 | 0,0E+00 |
| | 1,5 | 28,3 | 10,00 | 3 | 29,7 | 0,03 | 3 | 4,7E-02 | 28,3 | 28,3 | 28,3 | 4,67 | 3 | 0,0E+00 |

*Table 11. Computational results for n=20*

| Company | $\tau$ | MILP | | | CA | | | | SA | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $C_{\max}$ | CT (sec) | No. Batch | $C_{\max}$ | CT (sec) | No. Batch | Dev | Best $C_{\max}$ | Avg $C_{\max}$ | Worst $C_{\max}$ | Avg CT (sec) | Avg No. Batch | Dev |
| 1 | 0,5 | 63 | 5 | 9 | 66,5 | 0,03 | 10 | 5,3E-02 | 63 | 63,5 | 64,5 | 6,03 | 7,8 | 7,9E-03 |
| | 0,75 | 63 | 6 | 9 | 64 | 0,05 | 10 | 1,6E-02 | 63 | 63,7 | 64 | 6,07 | 9,7 | 1,1E-02 |
| | 1 | 68 | 10 | 9 | 75 | 0,05 | 10 | 9,3E-02 | 71 | 72,6 | 74 | 6,08 | 9 | 6,3E-02 |
| | 1,25 | 84 | 281 | 9 | 86,5 | 0,03 | 10 | 2,9E-02 | 84,5 | 85,4 | 86,5 | 6,49 | 9 | 1,6E-02 |
| | 1,5 | 94 | 121 | 7 | 98 | 0,05 | 10 | 4,1E-02 | 95 | 96,8 | 98 | 6,32 | 8,7 | 2,9E-02 |
| 2 | 0,5 | 40 | 10 | 6 | 40 | 0,04 | 6 | 0,0E+00 | 40 | 40 | 40 | 8,82 | 6 | 0,0E+00 |
| | 0,75 | 39 | 5 | 6 | 39 | 0,12 | 6 | 0,0E+00 | 39 | 39 | 39 | 9,05 | 6 | 0,0E+00 |
| | 1 | 40 | 15 | 6 | 40 | 0,05 | 6 | 0,0E+00 | 40 | 40 | 40 | 8,20 | 6 | 0,0E+00 |
| | 1,25 | 42 | 15 | 6 | 42 | 0,04 | 6 | 0,0E+00 | 42 | 42 | 42 | 8,04 | 6 | 0,0E+00 |
| | 1,5 | 45 | 26 | 6 | 45 | 0,05 | 6 | 0,0E+00 | 45 | 45 | 45 | 8,19 | 6 | 0,0E+00 |
| 3 | 0,5 | 42 | 25 | 5 | 43,6 | 0,07 | 6 | 3,7E-02 | 42 | 42,2 | 42,5 | 12,46 | 5 | 4,7E-03 |
| | 0,75 | 41 | 25 | 6 | 41,4 | 0,05 | 6 | 9,7E-03 | 41 | 41,2 | 41,4 | 14,82 | 6 | 4,9E-03 |
| | 1 | 41 | 5 | 6 | 42,2 | 0,06 | 6 | 2,8E-02 | 41,3 | 41,7 | 42,2 | 12,50 | 6 | 1,6E-02 |
| | 1,25 | 48 | 10 | 6 | 48,8 | 0,09 | 6 | 1,6E-02 | 48 | 48,3 | 48,5 | 17,29 | 6 | 6,2E-03 |
| | 1,5 | 54,7 | 95 | 6 | 55,7 | 0,04 | 6 | 1,8E-02 | 55,7 | 55,7 | 55,7 | 7,94 | 6 | 1,8E-02 |

*Table 12. Computational results for n=50*

| Company | $\tau$ | MILP | | | CA | | | | SA | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $C_{\max}$ | CT (sec) | No. Batch | $C_{\max}$ | CT (sec) | No. Batch | Dev | Best $C_{\max}$ | Avg $C_{\max}$ | Worst $C_{\max}$ | Avg CT (sec) | Avg No. Batch | Dev |
| 1 | 0,5 | 162,5 | 31 | 25 | 166,5 | 0,09 | 25 | 2,4E-02 | 162,5 | 163,3 | 164,5 | 19,25 | 22 | 4,9E-03 |
| | 0,75 | 166,5 | 286 | 25 | 166,5 | 0,07 | 25 | 0,0E+00 | 166,5 | 166,5 | 166,5 | 22,12 | 23,7 | 0,0E+00 |
| | 1 | 164,5 | 60 | 24 | 164,5 | 0,15 | 25 | 0,0E+00 | 164,5 | 164,5 | 164,5 | 18,68 | 24,7 | 0,0E+00 |
| | 1,25 | 184 | 1587 | 20 | 188,5 | 0,09 | 25 | 2,4E-02 | 188,5 | 188,5 | 188,5 | 17,67 | 23,8 | 2,4E-02 |
| | 1,5 | 220 | 821 | 21 | 220 | 0,07 | 25 | 0,0E+00 | 220 | 220,0 | 220 | 19,92 | 20,5 | 0,0E+00 |
| 2 | 0,5 | 98,3 | 45 | 14 | 98,3 | 0,05 | 16 | 0,0E+00 | 98,3 | 98,3 | 98,3 | 17,20 | 15,2 | 0,0E+00 |
| | 0,75 | 99 | 75 | 15 | 99 | 0,16 | 16 | 0,0E+00 | 99 | 99 | 99 | 15,71 | 15,5 | 0,0E+00 |
| | 1 | 98,3 | 70 | 16 | 98,4 | 0,09 | 16 | 1,0E-03 | 98,4 | 98,4 | 98,4 | 12,51 | 15,5 | 1,0E-03 |
| | 1,25 | 100 | 160 | 15 | 100,6 | 0,07 | 16 | 6,0E-03 | 100 | 100,3 | 100,6 | 25,43 | 13,7 | 3,0E-03 |
| | 1,5 | 110,3 | 28724 | 15 | 110,3 | 0,15 | 16 | 0,0E+00 | 110,3 | 110,3 | 110,3 | 21,16 | 15,7 | 0,0E+00 |
| 3 | 0,5 | 95 | 45 | 14 | 95,4 | 0,07 | 16 | 4,2E-03 | 95 | 95,3 | 95,4 | 26,03 | 15,3 | 3,1E-03 |
| | 0,75 | 95 | 35 | 15 | 95,4 | 0,05 | 16 | 4,2E-03 | 95 | 95,3 | 95,4 | 23,40 | 15,5 | 3,1E-03 |
| | 1 | 97 | 100 | 16 | 97,7 | 0,10 | 16 | 7,2E-03 | 97 | 97,3 | 97,7 | 34,00 | 16 | 3,1E-03 |
| | 1,25 | 105,7 | 3504 | 15 | 108,8 | 0,08 | 16 | 2,8E-02 | 108,3 | 108,5 | 108,8 | 39,62 | 15,7 | 2,6E-02 |
| | 1,5 | 112,7 | 28707 | 15 | 116,7 | 0,14 | 16 | 3,4E-02 | 116,7 | 116,7 | 116,7 | 47,23 | 15,5 | 3,4E-02 |

*Table 13. Computational results for n=100*

| Company | $\tau$ | MILP | | | CA | | | | SA | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $C_{\max}$ | CT (sec) | No. Batch | $C_{\max}$ | CT (sec) | No. Batch | Dev | Best $C_{\max}$ | Avg $C_{\max}$ | Worst $C_{\max}$ | Avg CT (sec) | Avg No. Batch | Dev |
| 1 | 0,5 | 293 | 26 | 49 | 302 | 0,20 | 50 | 3,0E-02 | 293 | 295,5 | 297,5 | 46,10 | 49 | 8,5E-03 |
| | 0,75 | 297 | 141 | 49 | 311,5 | 0,12 | 50 | 4,7E-02 | 298 | 301,4 | 304 | 41,54 | 49 | 1,5E-02 |
| | 1 | 296 | 1002 | 49 | 296 | 0,10 | 49 | 0,0E+00 | 296 | 296 | 296 | 54,73 | 49,2 | 0,0E+00 |
| | 1,25 | 338 | 28714 | 29 | 341 | 0,17 | 50 | 8,8E-03 | 338 | 339,3 | 341 | 50,88 | 49 | 3,8E-03 |
| | 1,5 | 398 | 28708 | 26 | 397 | 0,29 | 50 | -2,5E-03 | 397 | 397,0 | 397 | 54,68 | 50 | -2,5E-03 |
| 2 | 0,5 | 206 | 1712 | 32 | 206 | 0,10 | 33 | 0,0E+00 | 206 | 206 | 206 | 56,64 | 31,3 | 0,0E+00 |
| | 0,75 | 207 | 641 | 33 | 207 | 0,16 | 33 | 0,0E+00 | 207 | 207 | 207 | 50,40 | 31,5 | 0,0E+00 |
| | 1 | 206 | 321 | 32 | 206 | 0,10 | 33 | 0,0E+00 | 206 | 206 | 206 | 54,96 | 30,2 | 0,0E+00 |
| | 1,25 | 209 | 4655 | 29 | 209 | 0,10 | 33 | 0,0E+00 | 209 | 209 | 209 | 47,62 | 31,3 | 0,0E+00 |
| | 1,5 | 218 | 28709 | 21 | 213,7 | 0,30 | 33 | -2,0E-02 | 213,7 | 213,7 | 213,7 | 36,48 | 31,8 | -2,0E-02 |
| 3 | 0,5 | 197,3 | 245 | 31 | 198,3 | 0,22 | 33 | 5,0E-03 | 198 | 198,2 | 198,3 | 45,93 | 32,2 | 4,5E-03 |
| | 0,75 | 198,3 | 376 | 32 | 198,9 | 0,13 | 33 | 3,0E-03 | 198,3 | 198,8 | 198,9 | 39,93 | 31,5 | 2,5E-03 |
| | 1 | 200,3 | 6252 | 31 | 201,8 | 0,26 | 33 | 7,4E-03 | 201,2 | 201,5 | 201,8 | 37,50 | 31,75 | 6,0E-03 |
| | 1,25 | 204,7 | 28717 | 30 | 204,7 | 0,11 | 33 | 0,0E+00 | 204,7 | 204,7 | 204,7 | 36,06 | 32,8 | 0,0E+00 |
| | 1,5 | 225 | 28719 | 22 | 221,7 | 0,13 | 33 | -1,5E-02 | 221,3 | 221,6 | 221,7 | 32,63 | 32,7 | -1,5E-02 |

*Table 14. Computational results for n=200*

| Company | $\tau$ | MILP | | | CA | | | | SA | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $C_{\max}$ | **CT (sec)** | **No. Batch** | $C_{\max}$ | **CT (sec)** | **No. Batch** | **Dev** | **Best** $C_{\max}$ | **Avg** $C_{\max}$ | **Worst** $C_{\max}$ | **Avg CT (sec)** | **Avg No. Batch** | **Dev** |
| **1** | 0,5 | 617 | 2928 | 91 | 639,5 | 0,24 | 100 | 3,5E-02 | 623,5 | 624,9 | 625,5 | 96,70 | 96,8 | 1,3E-02 |
| | 0,75 | 619 | 7918 | 90 | 639,5 | 0,16 | 100 | 3,2E-02 | 628,5 | 630,2 | 632 | 113,40 | 98 | 1,8E-02 |
| | 1 | 643 | 28720 | 74 | 640,5 | 0,24 | 100 | -3,9E-03 | 634 | 637,9 | 640,5 | 116,23 | 99,2 | -8,0E-03 |
| | 1,25 | 740,5 | 28723 | 55 | 736,5 | 0,18 | 100 | -5,4E-03 | 735,5 | 736,3 | 736,5 | 105,98 | 98,2 | -5,7E-03 |
| | 1,5 | 859 | 28719 | 50 | 862,5 | 0,19 | 100 | 4,1E-03 | 860 | 861,2 | 862,5 | 112,67 | 98 | 2,6E-03 |
| **2** | 0,5 | 414,7 | 13658 | 58 | 415 | 0,36 | 66 | 7,2E-04 | 415 | 415 | 415 | 91,00 | 64,7 | 7,2E-04 |
| | 0,75 | 415,7 | 6227 | 62 | 416,8 | 0,33 | 66 | 2,6E-03 | 416,1 | 416,3 | 416,6 | 86,54 | 59,7 | 1,4E-03 |
| | 1 | 418,7 | 28729 | 62 | 419,2 | 0,29 | 66 | 1,2E-03 | 418,7 | 418,8 | 419,2 | 130,33 | 63,8 | 2,4E-04 |
| | 1,25 | 436,7 | 28734 | 54 | 415,7 | 0,26 | 66 | -5,1E-02 | 415,7 | 415,7 | 415,7 | 95,81 | 65,3 | -5,1E-02 |
| | 1,5 | 466 | 28729 | 50 | 433,7 | 0,36 | 66 | -7,4E-02 | 427 | 431,1 | 433,7 | 116,10 | 64,7 | -8,1E-02 |
| **3** | 0,5 | 413 | 20621 | 66 | 416,9 | 0,32 | 66 | 9,4E-03 | 414,5 | 415,6 | 416,5 | 98,56 | 63,5 | 6,3E-03 |
| | 0,75 | 416 | 6466 | 65 | 417,1 | 0,38 | 66 | 2,6E-03 | 416,9 | 417,1 | 417,1 | 151,48 | 65,7 | 2,6E-03 |
| | 1 | 411 | 28222 | 65 | 414,4 | 0,37 | 66 | 8,3E-03 | 413,7 | 413,9 | 414,4 | 103,76 | 65,3 | 7,0E-03 |
| | 1,25 | 463,7 | 28714 | 50 | 426,3 | 0,36 | 66 | -8,8E-02 | 424,6 | 425,9 | 426,3 | 111,95 | 65,2 | -8,9E-02 |
| | 1,5 | 510,3 | 28729 | 41 | 459 | 0,23 | 66 | -1,1E-01 | 458,3 | 458,9 | 459 | 101,15 | 65,5 | -1,1E-01 |