Universidade do Minho
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An Optimization Approach to the Tactical Production Planning in a Filling Company

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Aknowledgements

As I reach the culmination of my academic path, I am overwhelmed with a profound sense of accomplishment and gratitude. Completing this thesis means the end of a remarkable chapter in my life and represents the fulfillment of a long-held aspiration. This transformative journey has enriched me with invaluable experiences.

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STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.
I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho.

Resumo

No atual ambiente empresarial altamente competitivo, as empresas procuram melhorar a qualidade do produto, reduzir custos e atender às necessidades dos clientes. Sistemas eficazes de planeamento e controlo de produção desempenham, desta forma, um papel crucial no cumprimento destes objetivos e na melhoria do desempenho organizacional global. Ao recorrer a análises de dados e a métodos analíticos, as empresas otimizam o planeamento da produção, com especial ênfase no planeamento de médio prazo. Deste modo, é possível garantir uma utilização eficiente dos recursos, desde matérias–primas até à conversão das mesmas no produto final, ao mesmo tempo em que se atende às expectativas dos clientes quanto à entrega pontual. O planeamento da produção implica a tomada de decisão em diferentes níveis, exigindo a coordenação e a integração de diferentes funções organizacionais. Globalmente, a integração do planeamento da produção em vários níveis e funções é essencial para garantir a viabilidade dos planos e alinhá-los com os objetivos globais.

O presente estudo foi realizado numa empresa do setor de enchimento com o propósito de abordar os problemas identificados no planeamento da produção a médio prazo. Foi desenvolvido um modelo de otimização baseado em programação inteira mista para gerar planos de produção semanais num horizonte de 17 semanas. O estudo considerou duas fábricas com múltiplas linhas de produção e uma ampla variedade de produtos. O objetivo primordial passou por alocar os recursos de produção de forma eficiente e manter uma capacidade de produção equilibrada, capaz de responder à procura. No entanto, o modelo desenvolvido introduz um avanço significativo neste domínio ao incorporar um fator crucial: a disponibilidade de matérias-primas. Este aspeto distingue-o das abordagens existentes, uma vez que aborda o processo de planeamento da produção a montante, tendo em conta fatores como as encomendas futuras e as potenciais compras de matérias-primas. Adicionalmente, a metodologia engloba a definição do conceito de *safe quantity*. Este conceito corresponde à determinação da quantidade de cada ordem de produção que é seguro antecipar, tendo em conta a fiabilidade histórica do cliente, permitindo uma maior flexibilidade na produção e maior potencial de agregação de ordens.

A implementação das metodologias desenvolvidas, permitiram alcançar melhorias em ambas as fábricas. Os resultados iniciais sugerem que os planos de produção desenvolvidos acarretam um aumento na quantidade total produzida, conduzindo a uma redução de 3.4% e 10.1% no custo de produção unitário associado à Fábrica 1 e Fábrica 2, respetivamente. Para além disso, os planos de produção impactaram diretamente a gestão de componentes, resultando numa redução do tempo de atraso médio das ordens de produção.

Palavras-chave

Empresa de Enchimento; Planeamento Tático da Produção; Modelo de Otimização

Abstract

In today's highly competitive business environment, companies strive to enhance product quality, reduce costs, and meet customer demands. Effective production planning and control systems play a crucial role in achieving these objectives and improving overall organizational performance. By adopting data analytics and analytical methods, companies optimize their production planning, with a special emphasis on the medium-term aspect. This ensures efficient resource utilization, from raw materials to final product conversion, while also meeting customer expectations for timely delivery. Production planning involves decision-making at different levels, requiring coordination and integration across organizational functions. Integration of production planning across levels and functions is vital for feasible plans aligned with overall objectives.

The present study was conducted in a filling industry company to address the identified issues in production planning. A medium-term optimization approach was developed to generate weekly production plans, considering a horizon of 17 weeks, using a mixed-integer programming formulation. The study considered two facilities with multiple production lines and a diverse range of products. The objective was to efficiently allocate production resources and ensure a balanced production capacity to meet demand. However, the developed model introduces a significant advancement in the field by incorporating a crucial factor: the consideration of raw materials availability. This unique aspect sets it apart from existing approaches as it addresses the upstream production planning process, accounting for factors such as future arrivals and potential purchases of raw materials. Additionally, the methodology encompasses the definition of the safe quantity concept. This concept consists in determining the quantity of each production order that can be safely anticipated, considering the historical customer's reliability. This allows for greater production flexibility and elevates the potential for order aggregation.

The implementation of the developed methodologies has led to improvements in both factories. Initial results suggest that the production plans developed result in an increase in the total quantity produced, leading to a reduction of 3.4% and 10.1% in the unitary production cost associated to Factory 1 and Factory 2, respectively. Moreover, the production plans directly impacted raw materials management, resulting in a reduction in the average delay time of production orders.

Keywords

Filling Company; Tactical Production Planning; Optimization Model

Contents

ACRONYMS

ATP - Available-to-Promise.

BOM - Bill of Materials.

CRP - Capacity Requirement Planning.

ERP - Enterprise Resource Planning.

FAS - Final Assembly Schedule.

KPI - Key Performance Indicator.

LP - Linear Programming.

MILP - Mixed-Integer Linear Programming.

MOQ - Minimum Order Quantity.

MPR - Minimum Production Round.

MPS - Master Production Scheduling.

MRP - Material Requirements Planning.

MTO - Make to Order.

OEE - Overall Equipment Effectiveness.

SKU - Stock Keeping Unit.

WACC - Weighted Average Cost of Capital.

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1. Introduction

The present dissertation falls under the scope of the Master in Industrial Engineering and Management at the University of Minho. The thesis was developed during an internship in *LTPLabs*, an analytical management consultancy company, as part of a project with one of its clients. The purpose of this chapter is to give a general overview of the dissertation's subject and extent, problems that are tackled, project's objectives, and structure of the entire document.

1.1. Motivation

Regardless of the industry sector, all companies must build strategies to raise the quality of their products across a wide range, reduce costs through improved production planning and streamlined workflows, meet customer demands by investing in design upgrades and enhancements, and product development assets (Carravilha and Pinho de Sousa, 1995). As Jacobs et al. (2011) defends, the development of an effective and efficient manufacturing planning and control system is crucial for the prosperity of any goods producing company, since enhances the overall performance of the organization while, simultaneously, improves customer satisfaction.

The advent of a fourth industrial revolution has been facilitated by the integration of cutting-edge technology into production systems. This paradigm-shifting has driven companies to embrace automation technologies, resulting in improved task parameter management and real-time access to operational data (Rossit et al., 2019). As a result, there is a significant opportunity to harness these advancements to optimize decision-making processes by replacing laborious manual spreadsheets with highly efficient analytical tools (Vieira et al., 2019). Therefore, in a global marketplace with ever increasing competitiveness levels, companies seek to leverage the available data through the use of analytical methods and tools to improve their overall performance, aiming to secure a prominent position. Production planning stands out as one of the areas of greatest potential in the analytic sector and its proper implementation, with special attention to medium term planning, is critical to the success of any company.

Appropriate production planning results in the efficient and cost-effective acquisition, exploitation, and allocation of production resources to convert raw materials into final products. Furthermore, production planning directly impacts the service level that a company can provide to its customers, by delivering the finished products on time, meeting the established deadlines. A variety of organizational departments, including manufacturing, accounting, and marketing, are involved in making decisions on production planning. Commonly, production planning decisions are divided into three levels: strategic (long term), tactical (medium term) and operational (short term). There exists, consequently, the need to integrate and coordinate the different levels to guarantee the feasibility of the plans and coherence in fulfilling planning objectives (Misni and Lee, 2017).

The main focus of this thesis will lie on the medium term scope, more specifically on Master Production Scheduling and Capacity Planning. Tactical production planning focuses on determining the optimal levels of production, inventory, and labor, and capacity needs, in order to meet the imposed demands in each period, over the defined horizon (Jamalnia et al., 2017). Moreover, it is crucial to note that the developed methodology is closely linked to upstream production planning, as it directly incorporates considerations of raw material availability, future deliveries, and potential purchases. This integration ensures the feasibility of production by addressing critical factors that enable the availability of necessary inputs.

Nowadays, despite all the technology advancements and evolution, many companies still make this medium term planning based on empirical knowledge with insufficient analytically backed by a decision support system. Combining this factor with the intricate nature of the issue and the vast number of potential solutions, there is undoubtedly room for improvement. In this way, given the enormous potential to increase efficiency levels in these businesses, the study of optimization models applied to tactical production planning is a particularly pertinent topic.

1.2. Project Background

This dissertation was developed during a consulting project for a Portuguese company operating in the consumer goods industry, specifically in the filling sector. The company is a prominent international player in the contract manufacturing of a variety of products, including cosmetics, personal and home care, and over-the-counter pharmaceutical products. In the past year the company was responsible for producing more than half a billion units. With five filling plants, all of them with multiple production lines and a range of various products across more than 20 well-known brands, efficient production planning is, for them, of the utmost importance. The production planning evaluation project focuses on two of the five factories of the company under study, named Factory 1 and Factory 2 throughout this document.

An earlier diagnosis, conducted in the studied company, identified several changes and improvement opportunities. The *as is* weekly production planning process was strongly based in an empirical planning, lacking analytical support in the decision making process. Therefore, a set of four main opportunities was identified, related with demand planning, production planning, and procurement.

1.3. Project Objectives, Results and Timeline

This project aims to primarily develop and implement a production planning optimization model that allows to obtain weekly production plans for a time horizon of 17 weeks. The purpose of this tool is to improve the company's efficiency by minimizing overall production costs while fulfilling expected customer orders. The costs evaluated in this model are the following:

1. Plant opening and operating costs (costs of having a plant running);
2. Line operating costs (costs of having a line running, including utilities and maintenance);
3. Regular labor costs;
4. Overtime labor costs (for weekends and night shifts);
5. Order delay costs;
6. Costs of not delivering an order;
7. Production costs (costs of producing each product in each filling line);
8. Holding costs;
9. Warehousing costs.

Thereby, the model endeavors to minimize the overall costs associated with the production planning function by taking into account various pertinent constraints that encapsulate the company's operational environment and its established practices. These constraints encompass the requirements and limitations that arise from the company's specific operational context. The model incorporates sets of constraints pertaining to the following aspects:

1. **Customer orders management and production:** entail the responsibility of determining whether an order should proceed with production or be canceled. Additionally, if the decision is to proceed with production, it involves assessing the feasibility of delivering the order on the specified date or the need for a delay;
2. **Product management:** holds the responsibility of ensuring adherence to product specifications, such as Minimum Order Quantity (MOQ) and Minimum Production Round (MPR);
3. **Workforce management:** involves the process of determining the working schedule for each factory, ensuring compliance with the labor regulations in force in the country where the factory is located;
4. **Setup definition:** encompasses limitations related to the requirement of performing a setup whenever there is a change in the finished goods being produced on a specific filling line within a given week;
5. **Available capacity:** imposes limitations on the production of each filling line during each week, ensuring adherence to the allocated capacity in terms of hours. This includes considering the time required for production as well as the time dedicated to setups;

6. **Raw materials availability:** constrains production to the presence of adequate and required raw materials. The model permits production only when there are available raw materials, scheduled deliveries, or the option to place new orders;
7. **BOM recipes:** guarantee the accurate execution of the process for selecting the most appropriate recipe of raw materials among alternatives when producing goods. This ensures that only one recipe is chosen, taking into account the remaining productions and their specific requirements.

The process of setting and maintaining the model parameters will be conducted through an intuitive and interactive online interface, in order to facilitate the implementation of the model.

Furthermore, the concept of safe quantity is implemented, which aims to consider the possibility of anticipating certain quantities of orders from customers with more reliable historical forecast. As a result, the optimization module supports order aggregation of stable clients, thus capturing the benefits of aggregated batch productions, while accounting for raw materials and tactical constraints. The optimization model has additional benefits, which includes making it easier to generate alternative scenarios, assessing the impact of changes in tactical levers, providing a comprehensive view of the process and its associated costs, and ensuring complete visibility into raw material and workforce requirements.

The project also encompasses the development of a dashboard that enables the analysis, evaluation and monitoring of Key Performance Indicator (KPI) of industrial activity in an intuitive and visual manner, which are affected by the production planning module to assess the implementation success. Supplementary, the dashboard provides the ability to compare the different scenarios generated.

Figure 1 outlines the main stages of the project, with the respective dates and resulting deliverables, and milestones achieved. The project comprised four main phases: business information, production planning module, module validation, and test and monitorization. The initial phase, business information, consisted in the process of gathering all the relevant data, and implementing and tracking the appropriate KPIs. By the end of this phase, all the data inputs and outputs were automated and the KPIs were monitored. After that, the development of the model itself took place, followed by a testing phase where preliminary results were generated and validated with the client, using historic production planning, in order to perform the necessary adjustments to the model. The project also encompassed a follow-up period, where the module was monthly tested and monitored in the real company's environment, with the aim to obtain a stabilized process.

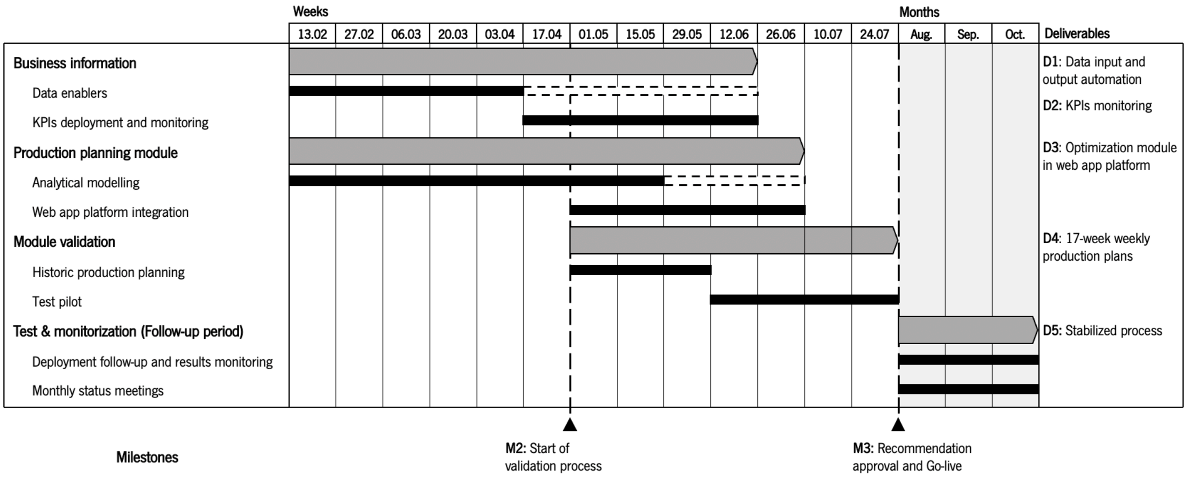

Figure 1: Project's timeline

1.4. Thesis Outline

The present dissertation is organized into six chapters, with the subsequent outline. Chapter 1. clarifies the purpose of this thesis, along with the problem's context and the primary goals to be pursued. Chapter 2. provides a theoretical background on themes pertinent to the work. A literature review about tactical production planning is initially provided, explaining the concept and providing an overview of the two problems that make up the study's focus – Master Production Schedule and Capacity Planning. Afterwards, a literature review on solving approaches and research on optimization methods for production planning is displayed, emphasizing linear programming. Chapter 3. gives a detailed description of the problem addressed in this project, as well as an overview of the company's planning context, indicating its performance and limitations. Furthermore, it encompasses pertinent exploratory analysis and presents the significant findings and challenges pertaining to the problem. Chapter 4. thoroughly elaborates on the devised methodology, including the mathematical formulation of the optimization method developed. Chapter 5. showcases the solution's results and presents the applied methodology's computational performance indicators. Lastly, Chapter 6. summarizes the main conclusions of the study, provides a reflection on the thesis' outcomes, and elaborates on suggestions for future work.

2. Literature review

The present chapter aims to provide a bibliographical review of the concepts that form the foundation for the accomplishment of this thesis. Section 2.1. provides a comprehensive overview of the fundamental aspects of production planning, presenting a general view of the discipline as a whole. Section 2.2. specifically focuses on tactical production planning, which is the primary level of production planning addressed in this project. The emphasis is placed on understanding the principal functions and concepts associated with tactical production planning, as it relates to the scope of this study. Additionally, delves into the two specific problems within the tactical production planning level that are the main focus of this research. Section 2.3. summarizes the main solving approaches applied to production planning, providing a classification of existing methods, with particular emphasis on the implementation of the linear programming method.

2.1. Production Planning

Over the past few decades, production planning has become increasingly important and has gained interest from both industry and academia. It is now considered one of the most crucial decisions faced by several companies (Demartini et al., 2021). To remain competitive in the current market, industrial organizations must prioritize quickly responding to the needs of their customers. Meeting customer needs and specifications in the shortest possible time and at a competitive price are critical factors in surviving in a highly competitive market. Therefore, creating a robust production plan is mandatory to accomplish these strategic objectives (Attia et al., 2021).

Production planning requires effective management of the diverse resources needed to transform raw materials into final products that fulfil the demands of customers in a resourceful way. Part of the production planning process involves preparing for the acquisition, distribution, and use of resources, including materials, machinery, and labour, in a competent manner. The goal of production planning is to reduce expenses, increase productivity, and enhance general performance throughout the entire production process (Díaz-Madroñeroa et al., 2014).

Efficient production planning ensures the cost-effective utilization of resources for transforming raw materials into finished goods. The decision-making process for production planning involves multiple functional units, including production, accounting, and marketing. Furthermore, production planning is crucial to ensuring that the production stage of the supply chain matrix runs smoothly and efficiently. This requires developing a production plan that accurately forecasts demand, allocates resources adequately, and minimizes waste and delays. In addition, to implement production planning, companies must also consider the integration of production in the supply chain matrix. Figure 2, inspired by the work of Meyr et al. (2000), provides a simplified overview of the entire supply chain, encompassing the production planning process, divided into three time periods - long term, medium term and short term.

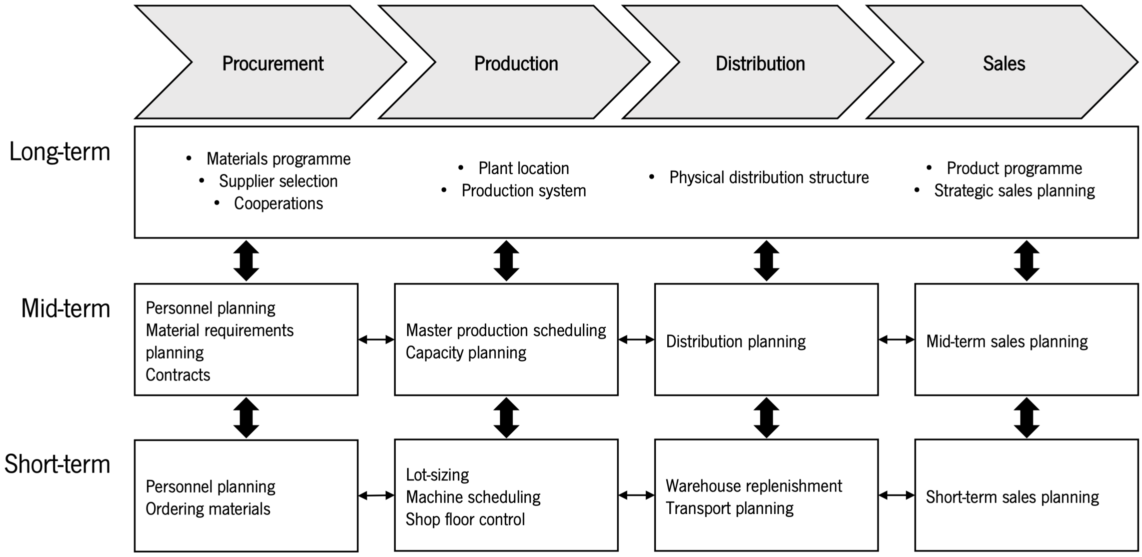

Figure 2: Supply chain matrix. Source: Meyr et al. (2000)

Managing production in the supply chain matrix is a fundamental element of effectively operating within the entire supply chain. Production plays a vital role in connecting the different stages of the supply chain, including procurement, distribution, and sales. The process begins with procurement, where the raw materials and resources needed for production are sourced and purchased. These materials and resources are transferred to the production stage, where they undergo various manufacturing processes to convert them into finished goods. Finally, at the sales stage, the products are advertised, marketed, and sold to consumers. Each stage of the supply chain matrix is dependent on the others, and any inefficiencies or problems in one stage can have significant impacts on the entire process (Bajgiran et al., 2015).

To connect the initial and terminal entities of the supply chain – supplier and customer – it is necessary to develop, invest and coordinate the production planning within a company. Therefore, the production planning process can be viewed as a framework divided into three phases, namely the front end, engine, and back end, as shown in Figure 3. The uppermost one, or front end, involves the set of activities and systems that aim to establish the overall direction of the organization for production planning. This phase encompasses demand management, sales and operations planning, resource planning, master production scheduling, and rough-cut capacity planning. Demand management ensures the coordination of all business activities that place demand on manufacturing capacity. Sales and operations planning aligns the plans of sales/marketing with the available resources. Master Production Scheduling (MPS), in turn, specifies the products, or end items, that will be produced. Finally, resource planning establishes the foundation to balance production plans with capacity.

Front end phase feeds directly the subsequent phase, the middle one, known as engine. The engine phase includes the application of the detailed material planning, which allows to plan the detailed capacity and obtain the global material and capacity plans. In a similar fashion, the outputs generated during the engine phase are commonly treated as inputs of the following phase: back end phase.

Lastly, the bottom one, or back end phase, receives the outputs of the prior phases (front end and engine) and depicts the production planning systems, specifically shop-floor systems and supplier systems. Shop-floor systems determines priorities for all shop orders at each work centre, allowing the execution of the properly scheduling. Supplier systems provide in-depth and updated information to the company's suppliers (Jacobs et al., 2011).

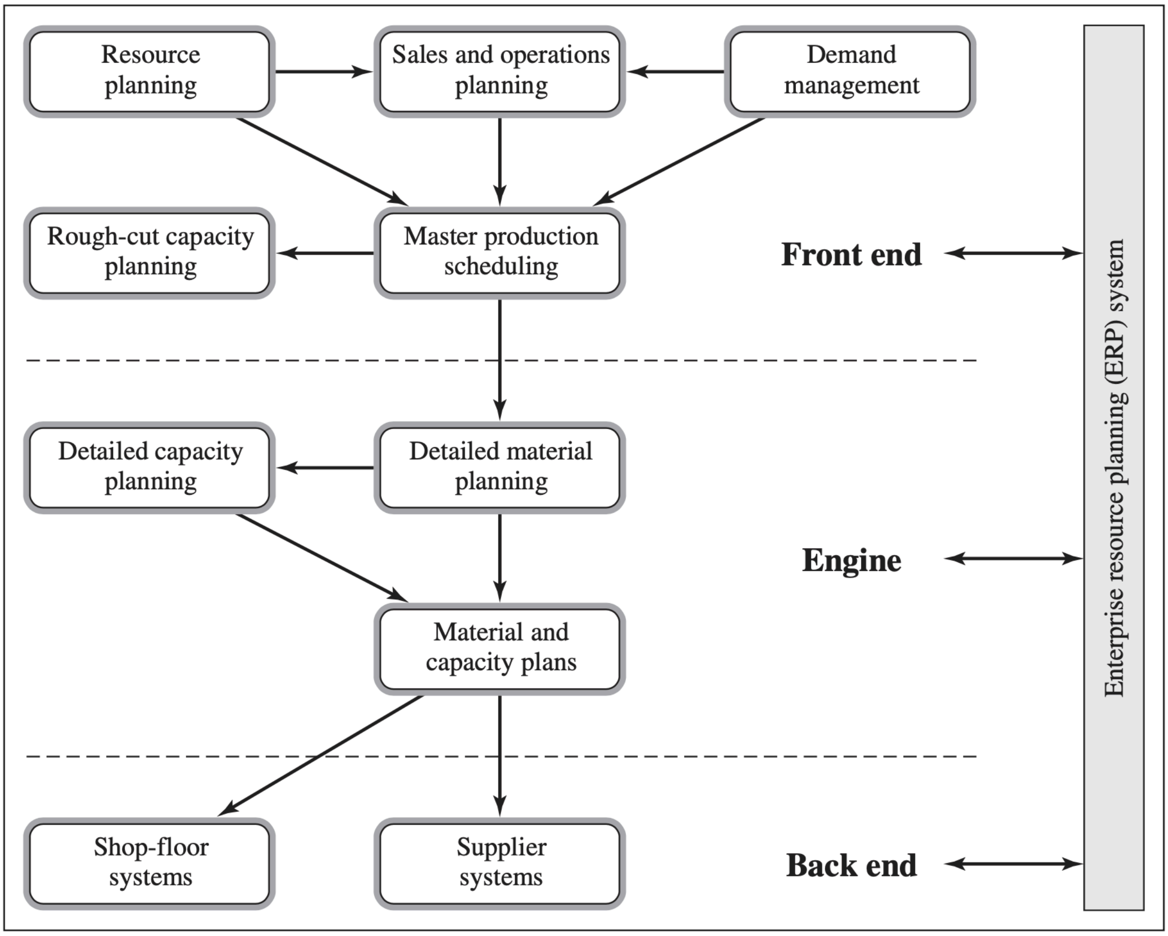

Figure 3: Production planning and control system. Source: Jacobs et al. (2011)

According to Thomas and McClain (1993), prior to developing the production planning, there are six vital decisions that need to be taken in order to ensure coherency and efficiency throughout the process of planning:

1. **The time unit:** concerns the time unit in which the production planning is applied and can vary from a shift-level production plan to a monthly production plan. It is very important to strike a balance between the level of detail required and the computational complexity involved. In one hand, smaller time units increase the level of detail but make the problem more computationally complex. Conversely, larger time units may reduce computational complexity, but they may also sacrifice detailed accuracy.
2. **The time horizon:** refers to the time period covered by the production planning. The duration of the time horizon varies depending on the level of planning being conducted. Typically, at the strategic level, the planning horizon ranges from one to two years. At the tactical level, the time horizon generally spans from six months to one year. Finally, at the operational level, the planning horizon encompasses a range of weeks up to six months. It is important to note that the specific time horizons can be influenced by factors such as the industry, company size, and specific requirements. Additionally, it is critical to consider the impact of seasonality in the production context, as the time horizon should encompass the different phases of seasonal demands.
3. **Level of aggregation of the products:** consider the possibility to aggregate products with similar characteristics into product families. However, it is also possible to implement a production plan with full detail to accurately analyse the involved costs. The suitable level of aggregation is directly related to the product line, the stability of the situation and the nature of costs.
4. **Level of aggregation of the production resources:** in a similar fashion, facilities, or production resources, namely production cells, production lines and workforce, can be aggregated in various ways. Therefore, it is possible to accommodate different levels according to the degree of detail required for production plans.
5. **Frequency of replanning:** frequently the production planning is done in a rolling mode. This means that, as time progresses, a plan that covers a time horizon T is implement for a certain number of time units. Then, the replanning occurs for the remain time units after an interval t (in most cases, it is every basic time unit or less often), in order to review and update the plan previously done.
6. **Number and structure of production plans:** several industrial companies often develop multiple production plans at different levels of aggregations. This occurs because different aggregated plans allow companies to evaluate and determine different critical factors, such as capacity and workforce necessities. Furthermore, having complementary distinct plans in place enables a robust analysis.

Typically, production planning is organized into a hierarchy that involves making decisions at three different levels – strategic, tactical, and operational (Torabi et al., 2010). The hierarchical structure of production planning has advantages as it allows for assigning specific decision-making tasks to different time periods. This approach involves categorizing decisions into long term, medium term, and short term periods, which enables companies to manage their resources more effectively and achieve their production objectives. By doing so, companies can better manage decision variables and simplify the decision-making process. Therefore, this hierarchical approach ensures that each decision is made with the appropriate level of detail and attention, ultimately leading to a successful production planning process (Altendorfer et al., 2016).

In the hierarchical approach, each level operates independently and feeds information into the next level. Therefore, as Carravilha and Pinho de Sousa (1995) points out, coordinating the three levels is mandatory to obtain viable plans and ensure that the planning objectives are achieved. Strategic planning is implemented to a long term horizon and addresses high level decisions, such as product design, capacity (equipment, buildings, suppliers, and so forth), plant layout, and human resource capabilities. The goal of strategic planning is to ensure that the organization's resources are optimally allocated to meet future demands and growth objectives. Tactical planning, which is focused on the medium term, aims to optimize decisions related to production, inventory, workforce levels, and overtime usage to absorb demand peaks. In this way, the main issue addressed in this level is related with matching supply and demand in terms of both product mix and volume. Tactical planning aims to achieve an equilibrium between product needs and available resources, aiming to reduce costs.

Finally, at the operational level, short term decisions are taken to optimize day-to-day operations, such as detailed scheduling of resources (time, material, people, equipment, and facilities) and sequencing of production jobs in order to meet production requirements. Operational planning aspires to maintain the smooth running of production by addressing any unforeseen issues promptly and minimizing disruptions to the production process (Misni and Lee, 2017).

2.2. Tactical Production Planning

Specifically, tactical production planning plays an important role in the overall production planning process since it is accountable for identifying the appropriate strategies and resources to accomplish production goals within the short to medium term time frame. Moreover, it involves analyzing data and making informed decisions based on organization's strengths, weaknesses, opportunities, and threats. Therefore, the tactical plan is closely aligned with the organization's overall strategy, and it provides a road map for achieving the overarching objectives. This production level receives information about the product portfolio, network structure, and capacity from the strategic level (Lindahl et al., 2023). Based on this information, it uses production planning to determine the appropriate inventory levels for all products and sets manufacturing targets for all facilities.

Tactical production planning encompasses several functions aimed at addressing diverse challenges. These functions include capacity planning, resource allocation, inventory management, production scheduling, and quality control (Jacobs et al., 2011; Bushuev, 2014). Firstly, capacity planning is a significant aspect of tactical production planning that aims to determine the necessary production capacity to meet demand and allocate resources accordingly, while avoiding overproduction and unnecessary expenses. Secondly, resource allocation refers to the process of distributing resources, including labour, machinery, and raw materials, among various production activities. The main purpose is to avoid over or under utilization. Inventory management is the process of tracking and controlling the levels of inventory in a production system, including how much inventory to maintain, when to maintain it, and how to manage it properly. The main objectives of this function are to balance inventory levels to avoid stockouts or excess inventory, minimize holding costs, and optimize material flow. Production scheduling involves the effective coordination of production activities and resource allocation to ensure the timely fulfillment of orders. Lastly, quality control is the process of creating monitor processes capable of ensuring that products meet the required quality standards. By efficiently managing these functions and concepts, organizations can optimize their production processes and ensure that they are meeting customer demand proficiently and competently.

Furthermore, tactical production planning endeavors to address various additional challenges, including the accurate prediction of customer demand to facilitate effective production planning and resource allocation. It involves prioritizing customer orders based on factors such as urgency, profitability, and available resources, as well as identifying and resolving bottlenecks and inefficiencies to minimize lead times and enhance customer satisfaction. Moreover, tactical production planning is responsible for seeking opportunities to minimize production costs while upholding product quality and meeting customer requirements. This involves effective coordination with suppliers, distributors, and other stakeholders to ensure a seamless flow of materials and information across the supply chain. Additionally, tactical production planning remains responsive to market fluctuations, customer preferences, and competitive dynamics by adapting production plans and strategies accordingly.

Revisiting the focus on Figure 3, it is crucial to recognize the close relationship between the three phases of production planning and control systems (front end, engine, and back end) and the tactical production planning. Specifically, the front end phase is aligned with the tactical planning level. During this phase, companies undertake activities such as demand forecasting, market analysis, and sales and operations planning. These activities play a vital role in determining production goals, resource requirements, and overall production strategies for the tactical planning level. The insights derived from the front end phase serve as valuable inputs for tactical planning, ensuring that production schedules are synchronized with customer demands and aligned with the objectives of the company.

Moreover, the engine phase of the production planning and control system exhibits a strong connection to the tactical planning level. Within this phase, companies concentrate on meticulous production scheduling, Material Requirements Planning (MRP), and capacity planning. These activities hold significant importance for the tactical planning level as they facilitate the translation of broader production goals into actionable and executable plans. The engine phase involves optimizing resource utilization, coordinating workflows, and effectively managing production orders based on the tactical decisions made at the planning level.

The back end phase is also intricately linked to the tactical planning level. In the back end phase, activities such as quality control, inspection, inventory management, and order fulfillment are conducted. These activities are significantly influenced by the tactical decisions formulated during the planning process. The back end phase plays a pivotal role in ensuring the effective execution of tactical plans and the fulfillment of customer orders in accordance with the established production strategies.

In essence, the front end, engine, and back end phases of production planning and control systems are interconnected with the significance of tactical production planning. These three phases form a robust framework that facilitates seamless alignment between strategic decision-making and operational execution. At the core of this interconnection lies the crucial role of tactical production planning, acting as a bridge between strategic objectives and day-to-day operations. By carefully considering factors such as demand forecasting, resource allocation, and production scheduling, tactical production planning enables organizations to optimize resources, effectively respond to market dynamics, and achieve precise production goals. It is through the domain of tactical planning that the broader strategic vision materializes and transforms into reality. Successful implementation of tactical plans not only ensures smooth production processes but also establishes the groundwork for sustainable growth, competitive advantage, and customer satisfaction. By aligning these phases, companies can navigate the complexities of production, adapt to changing market demands, and thrive in a dynamic business landscape. Tactical production planning serves as the cornerstone, empowering organizations to translate strategic visions into results and secure a prominent position in the marketplace.

The upcoming Sections 2.2.1. and 2.2.2. will delve deeper into the key functions of the production planning that are within the scope of the present study – Master Production Scheduling and Capacity Planning, respectively. Through a detailed exploration of these functions, it is possible to enhance the comprehension of their role in aiding organizations and in driving the success of production processes.

2.2.1. Master Production Scheduling

To succeed in distinct industrial sectors, organizations must develop strategies to enhance both quality across a broader range of processes, mechanisms, and products, and continuously adapting to evolving market demands and foster customer loyalty. Having processes that are either optimal or nearly optimal leads to quicker responses and overall economic benefits. This happens because of improved product quality, efficient resource use, better service, shorter waiting times, and lower inventory levels. In this way, is crucial to integrate various production plans levels to ensure plan feasibility and consistency. As a result, companies are recurrently investing on the elaboration of a detailed and improved MPS in order to achieve their production objectives (Carravilha and Pinho de Sousa, 1995).

Soares and Vieira (2009) defends that MPS is the most important activity in production planning and control and the key for a company to reach success. Master Production Scheduling serves as the link between the two top hierarchical levels – strategic and tactical – and organizes the company's production resources in order to satisfy the desired demand. Furthermore, MPS has a significant impact in the overall organization's performance since a well-executed master plan can strongly contribute to the company's success, whereas a poorly executed one can result in failure.

By applying the MPS is possible to adapt the aggregate plan into an operation plan, determine the quantity of finished goods that must be produced in the medium-term horizon, and establish the appropriate rates of production (Comelli et al., 2006). The proper development of MPS affects several departments in the organization, as it impacts the good use of production resources, the commitment to deliver customer needs, the balance between sales and production trade-offs, and the achievement of company's strategic objectives outlined in the sales and operations plan (Jacobs et al., 2011).

Furthermore, MPS is an essential step in the development, guidance and implementation of MRP, since MPS aids raw materials requirements production and thus facilitating its availability when later required (Sridharan et al., 1987). The MPS is decisive for ensuring that customer demand is met in the required service level and establishing a stable production plan in a MRP setting. As Serrano-Ruiz et al. (2021) states, it serves as a bridge between forecasting, order processing, and production planning activities, as well as a connection between detailed scheduling of raw materials and components.

The Master Production Schedule is a challenging task that requires identifying a production plan that is practicable while enhancing the operational efficiency and effectiveness. This, consecutively, leads to various benefits such as improved productivity, cost reduction, and increased revenue. The production plan created through MPS has a direct impact on an organization's operations, including production costs, inventory holding costs, and customer service level. Firstly, production costs are affected by the production plan as it specifies the resources, namely labour and raw materials, necessary to produce the intended output. Secondly, the MPS' production plan focuses on optimizing the overall production process to minimize waste and enhance efficiency, which in turn reduces inventory holding costs. Lastly, the production plan elaborated states the quantity and delivery dates of the products. In this way, by satisfying customer needs and ensuring delivery deadlines, organizations can improve their customer satisfaction and their overall business performance.

Closely related to MPS is the concept of Available-to-Promise (ATP), particularly in the context of production planning and inventory management. As mentioned earlier, the MPS outlines the production plan for final products based on customer orders and internal demand, including orders already placed. For each item, it describes the quantity and time of production in order to satisfy consumer needs and preserve ideal inventory levels. ATP, on the other hand, focuses on determining the quantity of products available to promise to customers based on the existing inventory and production capacity, by considering factors such as existing orders, production schedules, and inventory levels. In this way, ATP systems encompass a range of decisions concerning order capture activities, including order acceptance/rejection, due date setting, and order scheduling (Framinan and Leisten, 2010).

ATP serves as a software system, commonly integrated within Enterprise Resource Planning (ERP) systems, which focus on assessing the availability of finished goods at specific future time points (Pibernik, 2005). As affirmed by Jeong et al. (2002), the fundamental aim and outcome of ATP activity lie in furnishing customers with a definitive commitment regarding the delivery date for their orders.

Clearly, effective decision-making is of utmost significance. By implementing a successful ATP procedure, companies are able to predict order completion times with accuracy and make the best use of its manufacturing capabilities, ensuring that the company's customers receive their orders as soon as they are requested (Jeong et al., 2002).

In essence, the MPS establishes the production plan, while ATP verifies the feasibility of fulfilling the promised quantities of products by considering the available inventory and production capacity. The ATP calculation takes into account the production output from the MPS and subtracts any existing commitments to determine the quantity available to be promised to new customers. Through the integration of MPS and ATP, organizations can proficiently oversee their production and inventory levels, make realistic delivery promises to customers, and maintain optimal resource utilization.

2.2.1.1. Main Functions of Master Production Scheduling

Master Production Scheduling is a critical aspect of tactical production planning that helps organizations bridge the gap between their long term strategic plans and their day-to-day operational activities. The main functions of MPS can be grouped into three distinct branches, which are developing the production plans in order to respond to demand, supporting the sales and operations department, and establishing the required capacity to be able to execute the outlined plans.

Firstly, MPS involves developing a viable and detailed plan for the production process based on the organization's overall demand and available resources. The finite planning horizon, usually less than two years, is divided into distinct time periods. Thus, the main function of MPS is related with creating a thorough production plan that outlines the products that must be produced to meet customer demand, as well as the respective quantities and delivery dates, without backlogs and stock outs (Kimms, 1998).

Secondly, and according to Jacobs et al. (2011), MPS is the disaggregated version of the sales and operations plan, outlining the specific final products that will be manufactured. In this context, the MPS entails a function of supporting the sales and operations plan, since, at the conceptual level, it translates the company's sales and operations plan into a plan to produce specific products. On the medium term, MPS should aim to provide sales and operations department with a reasonable degree of flexibility while staying within the budget defined.

Lastly, and as it is possible to confirm in the Figure 3, Master Production Schedule is directly related with the development of a rough-cut capacity planning, and can be considered the primary information source for the capacity planning. Pursuant to Wortmann (1983), MPS is not a rough estimate of demand that is adjusted based on inventory and open orders. On the contrary, it is a particular production order that bypasses the calculations used in MRP, which determine the net inventory needed and lot sizes for production. Hence, the MPS should be realistic and acknowledge constraints in terms of capacity, materials, and suppliers' limitations, and costs of production. Furthermore, is imperative that MPS weigh the strategic decisions made by the top-management level reflected in aggregate production level, inventory target, production efficiency, flexibility to adapt and ability to respond to changes in the market, and desired service levels.

The MPS receives as an input the expected demand, which includes sales forecast, production forecast, customer orders, branch warehouse demands, and interplant orders. Therefore, creating a robust MPS is of the utmost importance for an organization since it helps and facilitates the negotiations with sales and promotes the coordination between departments in order to establish balanced workloads. The creation of an MPS considers conflicting objectives, such as maximization of service levels, efficiently utilizing resources, and minimization of inventory levels. It evaluates various relevant production aspects, including materials, capacity, time, and costs (Soares and Vieira, 2009).

2.2.1.2. Strategies of Master Production Scheduling

As specified in Blackstone and Cox (2014), the MPS is an organization's aspect determined within the context of Supply Chain planning environment, that considers four significant elements:

1. **Strategy adopted:** the MPS can be implemented taking into account several distinct strategies, namely make-to-stock, assemble-to-order, make-to-order, and engineer-to-order.
2. **Number and type of involved stakeholders:** entities, whether external or internal, that have a particular interest or concern in a specific company or project.
3. **Structure:** organization's system is mainly a hierarchy with its tiers and relations, where the entities involved are arranged vertically in different levels (Serrano-Ruiz et al., 2021).
4. **Nature of activities:** can be related with production, distribution and/or procurement.

Focusing the attention on the first element – strategy adopted to implement the MPS – it is important to clarify and distinguish the various production strategies practiced when applying and developing the plans created by the MPS. Overall, the MPS strategy chosen by an organization depend on the level of demand variability, the complexity of the production process, and the level of customization carried out (Wortmann, 1983).

- **Make-to-stock:** production strategy where standard products are manufactured in advance and kept in stock, ready for sale, and where the MPS-items are end-items. This strategy is frequently adopted by companies with accurate demand forecast, to match inventory with anticipated consumer demand;
- **Assemble-to-order:** is similar to make-to-stock strategy in the sense that both refer to situations where standard products are manufactured in advance. However, in assemble-to-order strategy, the MPS-items are not end-items, since the process of assembly into finished products happens just after specific customer orders are received. Therefore, one basic type of product can undergo several changes and acquire distinct final characteristics. Within this context, the MPS is structured around the components/sub-assemblies/modules, giving a thorough schedule for the finished items depending on the orders received, allowing for flexibility in the final configuration. This near-term plan is commonly known as the Final Assembly Schedule (FAS) and it exhibits a significant association with the assemble-to-order and make-to-order environments;
- **Make-to-order:** manufacturing strategy that involves producing goods only after receiving customer orders. The products are manufactured and customized to meet specific customer needs. Within the make-to-order setting, the MPS plays a crucial role in establishing the immediate delivery schedule for final products, which is customized according to the specific orders received. In this context, the FAS holds significant importance as it takes meticulous consideration of the common raw materials with lengthy lead times;
- **Engineer-to-order:** this approach enables the production of goods entirely custom-made without pre-designed components and involves processes such as research, prototyping, and testing. Engineer-to-order differs from the make-to-order strategy in that, upon receiving an order, the specifications of the order are not known in detail.

In conclusion, in a rapidly evolving environment, the success of a manufacturing organization is closely associated to the efficiency and optimization of its production planning and implementation. In this context, MPS is one of the key activities for the company's prosperity. By linking the strategic and tactical levels, and providing a detailed and integrated production plan that considers all the relevant factors, MPS helps organizations achieve their production goals and effectively meet customer demand and needs (Soares and Vieira, 2009).

2.2.2. Capacity Planning

The production planning system has a fundamental role in efficiently managing the flow of material, the utilization of people and equipment, and in respond to customer requirements by utilizing the capacity of facilities and suppliers. As Jacobs et al. (2011) states, production planning is typically comprised of two main activities: materials planning and capacities planning. The two must be coordinated and synchronized to achieve maximum outcomes, based on the managerial perception of market demands. In this way, capacity planning is required to implement and obtain the adequate production plan.

Capacity planning evolves determine an organization's capacity needs and developing a plan to meet those needs. This is possible by ensuring feasible production plans, production system constraints and demands, and the presence of the right resources – people, equipment, materials – available at the right time (Larsson and Fredriksson, 2019). Cheraghalikhani et al. (2019) describes capacity planning as a challenging problem due to the necessity of managing and coordinate interdependent factors to ensure that company can adequately satisfy customer needs. Furthermore, the outcomes of the capacity planning process should not only be used for production purposes, but also to provide feedback on tactical plan feasibility.

According to Carravilha and Pinho de Sousa (1995), capacity planning relies on the confirmation of customer orders, which means that cannot be planned too far in advance. Therefore, it is fundamental to consider and evaluate the option of adopting the use of non-regular capacity. In this way, it allows flexibility of capacity in order to meet customer demand. Under this scenario, the basic techniques for adopting capacity flexibility are related to using overtime hours, hiring personnel, implement temporary labour, subcontracting and changing inventory levels (Nunes de Carvalho et al., 2015).

Additionally, capacity planning is dependent on the appropriate level of detail for each planning horizon. Ensuring consistency throughout the different levels is a noteworthy issue since, commonly, capacity planning follow a hierarchical structure, where long term planning is performed at an aggregated level, while short term planning is carried out at a detailed level (Wortmann et al., 1996).

2.2.2.1. Structure of Capacity Planning Decisions

As mentioned earlier in Section 2.2.2., the capacity planning process can be viewed from a hierarchical structure point of view, consisting of five main levels – resource planning, rough-cut planning, capacity requirements planning, finite loading, and input/output analysis. These levels of capacity planning cover diverse time periods and decision-making processes, ranging from a high-level aggregated plan to the detailed scheduling decisions related to specific machines and tasks. Figure 4 depicts the referred hierarchical capacity planning structure.

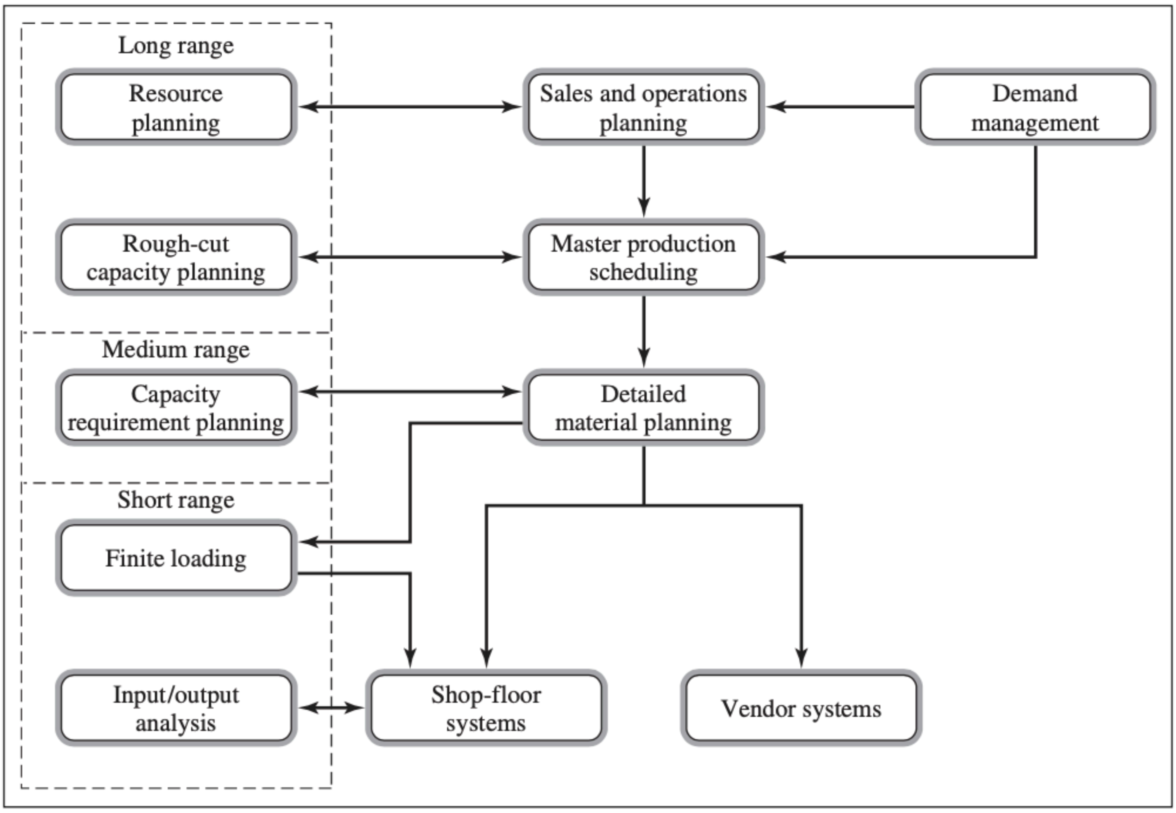

Figure 4: Hierarchical structure of capacity planning. Source: Jacobs et al. (2011)

As shown in Figure 4 and stated in Jacobs et al. (2011), capacity planning decisions follow a basic hierarchy structure where the long range planning establishes limitations on medium range capacity planning, which in turn constraint the specific scheduling and implementation of tasks on the production floor. Furthermore, other production planning modules and systems are dependent and directly affected by the five levels of the capacity planning process.

- **Resource Planning:** it is the most highly aggregated and longest range capacity planning decision. Resource planning is responsible for convert the output data from sales and operation plan into aggregate resources, for instance total labour hours, floor area, and machinery usage. Therefore, this decision needs to be closely linked to sales and operation planning module;
- **Rough-cut Capacity Planning:** the primary input of rough-cut planning decision is the plan developed by the master production schedule. Several techniques can be implemented to estimate the rough-cut capacity requirements, namely capacity planning using overall factors, capacity bills, and resource profiles. These techniques enable modifications to the resource level or material plan to guarantee the successful execution of the MPS;

- **Capacity Requirement Planning:** this technique allows firms to develop more comprehensive and detailed capacity plans. Capacity Requirement Planning (CRP) provides organizations with precise plans based on the production factors, such as work-in-progress, routing, scheduling recipes, and planned orders. A valuable input to this technique is the time-phased material plans produced by the MRP. In addition, the chief output of CRP technique is the information that enable organizations to estimate the necessities for machine centres and labour capabilities and expertise;
- **Finite Loading:** it is also seen as a shop scheduling process, and for this reason is part of both production activity control and capacity planning procedure. This technique is commonly implemented through the use of advanced production scheduling. Thereby, contrary to the previous approaches, considers adjustments to the elaborated plans, neglecting the utilization of planned capacity. By applying the finite loading technique each job is scheduled with precise timing on every work centre, rather than being scheduled in a more general manner;
- **Input/Output Analysis:** this methodology provides a framework to tracking and monitoring the real-time consumption of capacity when implementing the detailed and in-depth material planning. The results obtained in the production activity control supports this analysis, which is strongly connected to the shop-floor execution systems. By conducting an input/output analysis, it is possible to detect situations where actual shop performance differs from the planed one and make necessary updates to the capacity plans accordingly and in the planning factors employed.

It is important to highlight in the diagram of Figure 4 the presence of double-headed arrows connecting resource planning with sales and operation planning, rough-cut capacity planning with master production scheduling, capacity requirement planning with detailed material planning, and input/output analysis with shop-floor systems. These linkages represent the correlation between the capacity required and the capacity provided and available to carry out a particular material plan. Ensuring a harmonious correspondence between the two capacities is crucial and determinant for the efficient implementation of the plan. Contrary, without this correlation the plan will be unfeasible on inefficient.

In essence, the main aim of capacity planning techniques is to estimate the necessary capacity levels to meet future requirements projected with enough lead time to ensure that the organization can fulfil those requirements. Moreover, capacity planning involves dealing with a trade-off given that, on one hand, insufficient capacity can result in poor delivery performance, escalating work-in-progress, and dissatisfied manufacturing personnel. On the other hand, having more capacity than required could bring about unnecessary expenses that can be minimized. Hence, the second objective of the capacity planning process is to guarantee flawless execution of the plans to avoid unexpected outcomes. In order to better establish and implement the capacity plans, the resource and production planning process ought to be accurately executed. Additionally, capacity not only should be planned, but also monitored and controlled to ensure its stability and maintenance.

2.3. Solving Approaches Applied to Tactical Production Planning

It is extremely difficult to organize and manage inventories and production resources in a cost-effective manner. There are numerous variables at play, some of which are stochastic, and interactions between all of these variables must also be considered (Williams, 1984). As a result, several companies in the industry sector have employed optimization models to address specific issues. This occurs because it is becoming increasingly challenging to distribute the available resources to the various activities in a way that is most productive for the company as a whole, as complexity and specialization rise inside an organization (Hillier and Lieberman, 2010). Therefore, and with the aid of the ongoing study in this area, the complexity of the models and the methods for solving them have advanced through time, in line with the development of hardware and software tools (Putnik et al., 2018).

Production planning problems can be developed and solved using the rich formalism of optimization. The models, which are integrated into simple decision support systems, can give production managers the tools to assess their issues more thoroughly, boosting net revenues or cutting expenses. Developing efficient methods for coordinating and integrating a wide range of production processes is a key goal when developing an optimization model for production planning. Typically, production planning models consider planning time frames of one month to one year – tactical or operational levels –, are aggregate in nature, and attempt to explain significant portions of the production environment (Shapiro, 1989).

2.3.1. Classification of Optimization Methods

The interest in optimization methods has grown massively in recent years, stimulating the use of many different algorithms. The optimization models can be categorized in several optimization algorithms, according to the focus and characteristics of the algorithm (Amiri et al., 2017). Figure 5 shows the possible classification of optimization methods.

In line with the Figure 5, Amiri et al. (2017) states that the main division of the optimization models is between exact and approximate methods. As the name suggests, exact optimization methods aim to find the exact and best possible solution to a certain mathematical problem. On the other hand, approximate methods differ from the exact ones in the precise level required, since approximate optimization models aspire to determine a solution that is close to the optimal, but not necessarily the best possible. These algorithms are usually designed to obtain very good quality solutions in limited computational time.

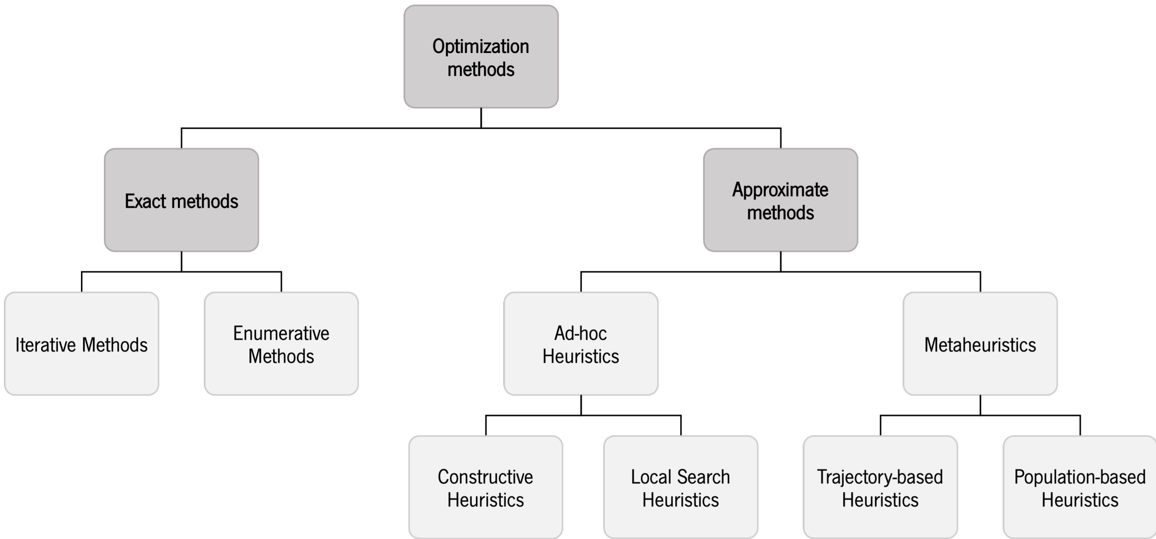

Figure 5: Optimization methods. Source: Suroliya et al. (2014) (adapted)

Iterative and enumerative methods are two types of exact methods used to solve optimization models. Firstly, iterative methods start with an initial solution that is refined in each iteration until the solution converges to a specific value – the optimal solution. The main benefit of the iterative methods is being applicable to complex problems because can converge quickly to the optimal solution. Secondly, the enumerative methods involve examining all possible solutions and selecting the ideal one. However, the solutions retrieved by this method grows exponential with the problem size, becoming, then, impractical for some contexts.

Approximate methods are grouped in two main categories – ad-hoc heuristics and metaheuristics. Ad-hoc heuristics are considered problem dependent since they refer to a problem-solving technique developed specifically for a given context and problem. The foundations of ad-hoc heuristics rely on common sense and experimentation (trial and error). This technique can be divided in constructive heuristics, which their goal is to construct a solution on a step by step basis that follows a set of rules, and local search heuristics, where an initial and admissible solution is improved through successive small changes. In contrast, metaheuristics are procedures that operate at a higher level to identify, generate, or select a heuristic that can offer an acceptable solution. Metaheuristics encompass two distinct methods – trajectory-based and population-based – where the primary contrast is that trajectory-based algorithms employ a single agent that follows a single path with iterative improvement, whereas population-based algorithms use multiple agents tracing different paths in order to reach the optimal solution.

2.3.2. Linear Programming

As Putnik et al. (2018) points out, problems in engineering are usually hard to be modeled due to the complex nature of these problems and the fact that they must depict real-life problems with a great deal of specificity. Over the last years, mathematical programming software has made significant progress, enabling the solution of very large and complex models. Nowadays, mathematical programming is not only applied to formulating strategic production planning models, but also for producing satisfactory solutions to the problems. For this reason, mathematical programming has become a valuable tool for most companies in the industry sector (Martínez-Costa et al., 2014). All optimization models mentioned in the previous sections lean on mathematical programming to reach the best possible solution as determined by objective functions while staying within the boundaries of problem constraints (Snyman and Wilke, 2018).

In the field of optimization through mathematical programming, two major groups can be found: linear programming and non-linear programming. The main difference between the two types relies on the mathematical functions used to describe the problem, specifically the objective function and the constraints. As the names suggest, linear programming are the models in which the constraints and objective functions are expressed by linear combinations of the decision variables. In contrast, non-linear techniques involve more complex functions that implies non-linear relationships between decision variables (Iqbalm et al., 2014).

Figure 6 shows the types of mathematical programming, both linear programming and non-linear programming, according to the nature of the problem's decision variables. The decision to adopt one type of approach should depend on the nature of the studied problem and on the specific variables involved.

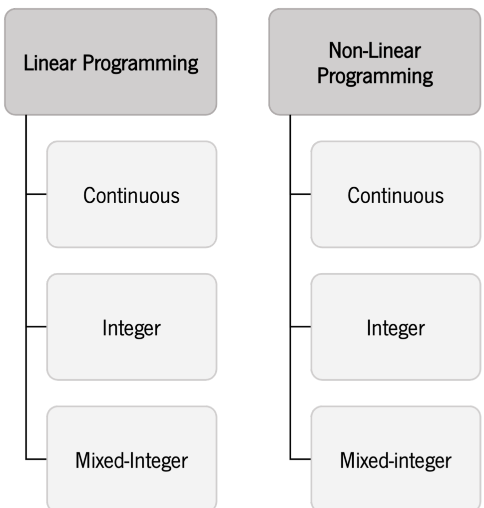

Figure 6: Types of mathematical programming methods. Source: Iqbalm et al. (2014) (adapted)

As Figure 6 shows, the decision variables encompassed by the mathematical programming models can be of three types, namely continuous, integer, and mixed-integer.

- **Continuous:** optimization model that includes decision variables that can assume any real value;
- **Integer:** model that incorporates decision variables that are restricted to integer values;
- **Mixed-Integer:** optimization model in which at least one decision variable is integer and others are continuous.

According to Hillier and Lieberman (2010), the formulation and implementation of a mathematical model involves six sequential and fundamental steps:

1. Define the problem of interest and gather relevant data;
2. Formulate a mathematical model to represent the problem;
3. Develop a computer-based procedure to determine solutions;
4. Test the model and refine it as needed;
5. Prepare for the ongoing application of the model as prescribed by management;
6. Implement.

Linear Programming (LP), in particular, and as the focus of the study, is considered by Silver (1976) as the most extensively studied technique in the field of operational research. Essentially, a LP model consists of determining the optimal value of multiple non-negative variables in order to minimize/maximize a linear function of these variables, subject to diverse linear constraints placed on the variables (Lindahl et al., 2023). Therefore, when formulating a LP model, it is mandatory to be aware of the key concepts present in the Table 1 (Hillier and Lieberman, 2010).

Furthermore, in order to be properly formulated and applied, every basic LP model needs adhere to four mathematical properties which should be highlighted – proportionality, additivity, divisibility, and certainty. Firstly, proportionality means that as the value of a decision variable increases/decreases, the impact on the correspondent addend of the function also increases/decreases in a linear fashion. Secondly, additivity implies that every function in a LP model can be formulated as the sum of the multiplication of one decision variable by the associated parameter. Thirdly, divisibility states that the decision variable in a LP model may take on any values that fulfill the requirements for functional programming and non-negativity constraints. Lastly, the certainty property ensures that the value assigned to each parameter is assumed to be an established value (Hillier and Lieberman, 2010).

Table 1: Linear programming key concepts

Concept	Definition
Decision variables	Variables whose respective values are to be determined
Objective function	Mathematical function of the decision variables used to determine a suitable measure of performance
Constraints	Restrictions on the permissible values for decision values, typically by means of inequalities or equations
Parameters	Constants present in the constraints and objective function
Model validation	Refining a model through a series of evaluations and adjustments to enhance its validity
Retrospective test	Entails reconstructing past events using historical data and evaluating the performance of a model and its solution

Considering the linear solving approaches applied to the context of production planning, it is important to understand the basic assumptions made, in an effort to make the model amenable to be formulated and implemented. Silver (1976) underline six assumptions made.

1. Market demand is deterministic.
2. Production costs in any given planning period are strictly linear or are piecewise linear.
3. Costs incurred as a result of changes to production rates in any given period are also linear or piecewise linear.
4. Inventory should be limited over the entire planning horizon.
5. Carrying costs for inventory are known for each period in the planning horizon.
6. Backorders may or may not be allowed.

However, the concepts underlying these assumptions neglect some real-life factors since are based on mathematical and theoretical concepts. For example, in a real production environment, is very hard for managers to predict future events and future demand with absolute certainty. Moreover, there is no guarantee in the industry sector that all costs are linear or that it would be ever appropriate to ensure that they are. Nonetheless, Linear Programming is capable to generate satisfactory solutions for real production planning contexts, even applying the mentioned assumptions (Nam and Logendran, 1992).

2.3.3. Application of Linear Programming in Production Planning

In addition to the inherent constraints imposed by production capacity, typical production scenarios include a range of other limiting factors. These comprise restrictions pertaining to the availability of raw materials, variability in setup times depending on the sequence of production, as well as prescribed minimum and maximum inventory thresholds. Moreover, the introduction of flexible routing, where a given quantity can be scheduled across multiple production resources, further intensifies the complexity of the process (Vieira and Favaretto, 2006). Hence, industrial production planning optimization is a prominent and rapidly advancing research field. It encompasses various approaches, including both exact and non-exact methods, and has given rise to highly effective optimization tools. Researchers continue to explore these approaches to enhance the efficiency and effectiveness of production systems in diverse industries. Particularly, in recent years, the application of linear programming techniques in production planning has been extensively studied and has brought about fundamental transformations in how businesses manage their manufacturing operations (Vieira et al., 2019).

By employing mathematical modeling and optimization methods, LP enables companies to make data-driven decisions, streamline production schedules, minimize costs, and maximize overall efficiency. This analysis highlights the advantages and potential of applying LP to production planning, demonstrating how it can be an effective tool for boosting operational efficiency and driving sustainable long-term corporate growth. The focus on LP methods stems from their ability to effectively address complex optimization problems inherent in production planning. As a result, it becomes imperative to delve into the outcomes and conclusions drawn from the studies made in this field, as they shed light on the efficacy and practicality of utilizing LP algorithms in tactical production planning.

This section delves into the practical application of LP, specifically MILP, in the realm of production planning within real-world production scenarios. It highlights the pivotal role of MILP in achieving optimal resource allocation and operational optimization. It is worth noting that in the production planning environment, MILP models are more commonly encountered due to the nature of the decisions that need to be made. The presented literature review primarily examines MILP-based approaches for the offline production planning problem. However, it is important to mention that other solution methods, including heuristic rules and metaheuristic algorithms, will also be briefly discussed for comparison purposes.

Firstly, the analysis conducted by Guzman et al. (2022) concludes that LP models, in particular MILP models, have been extensively employed in addressing production planning, scheduling, and sequencing problems, while Torkaman et al. (2018) and Bashiri et al. (2012) further supports this finding by highlighting the effectiveness of the mentioned approach in identifying superior solutions. However, it is important to note that the considerable time required to obtain these solutions poses a significant limitation, particularly when dealing with real-world problems of big instances, characterized by large dimensions and extensive datasets.

The research carried out by Soares et al. (2022) focuses on a case study that introduces an optimization model for production planning and scheduling within the tile industry. This model was specifically designed to address a production environment involving multiple product lines, where the setup time remains consistent regardless of the product sequence. The products are categorized into families, enabling batches to be processed on a production line without significant setup delays between jobs. The primary objective of the model is to minimize both the overall completion times of the production schedule and the total time spent on family setups. The study concludes that LP, particularly MILP, demonstrates the ability to generate high-quality solutions. However, it also acknowledges the challenge of achieving optimal solutions for real-world problems due to the substantial computational time required. Additionally, the development of a decision support system enables the attainment of similar solutions to those obtained manually but in a significantly shorter time frame.

In a study conducted by Oğuza et al. (2010), the authors investigated an environment characterized by Make to Order (MTO) operations. Within this context, the objective was to determine the optimal acceptance or rejection of orders based on factors such as production capacity, current workload, and profitability of each customer contract. The study focused on addressing the challenges associated with sequence-dependent setup times and aimed to maximize the overall profit. The research considered each order's due date and deadline, with tardiness penalties incurred for orders not completed before their due dates and zero profit for orders exceeding their deadlines. To address this problem, the researchers proposed a MILP model and developed three heuristic algorithms as alternative solution approaches. The study analysed the average performance across various instance types and revealed a consistent trend across the four approaches studied: as the problem size increased, the effectiveness of the methods decreased. Larger problem sizes posed challenges for achieving desirable outcomes, as the methods demonstrated diminished efficiency.

Georgiadis (2021) dedicates and elaborates on extensive research about the current topic, which focuses on the integrated optimal production planning and scheduling of breweries. Through his study, the author successfully demonstrates the superiority of the developed MILP model when compared to other existing approaches documented in the literature. Furthermore, to tackle the complexities associated with large-scale problems, Georgiadis (2021) introduces a novel two-step decomposition algorithm. These significant outcomes not only serve to validate the effectiveness of the proposed methodology but also underscore its potential for effectively addressing practical production planning and scheduling challenges.

The research undertaken by Belil et al. (2018) utilized MILP model to address the tactical planning problem within a multi-facility production, inventory, and distribution system in the chemical sector. The primary goal was to maximize the rate of demand satisfaction while minimizing inventory levels. The experimental studies shed light on the effectiveness of their proposed model in solving real-sized problems within reasonable time frames. Furthermore, the model demonstrated its flexibility and potential for extension to accommodate different time periods and product variations. By providing a formal approach that optimizes production, inventory, and distribution considerations, this research contributes to enhancing decision-making processes in the chemical industry.

In their study, Steinrücke and Jahr (2012) present a multi-period MILP model that addresses the complexities of multi-site production, distribution, and transportation planning. The model incorporates a complex Bill of Materials (BOM) and additional capacity planning. The research focuses on a real-world case study in the industrial transformer production for wind power plant locations. The study demonstrates that the model can serve as a robust decision support by providing tactical plans for the supply chain network. The findings highlight the effectiveness of the MILP model in improving decision-making processes and facilitating collaborative coordination within complex supply chain systems.

The study conducted by Mestry et al. (2011) revolves around the development of an optimization model within a MTO environment, specifically aiming to address the challenges of production and capacity planning. What distinguishes this study from previous research is its meticulous consideration of various factors that significantly contribute to the inherent complexity and difficulty in accurately modeling the problem. Notably, these factors encompass non-regular capacity requirements, such as overtime, and the potential utilization of outsourcing to accommodate additional work hours. By incorporating these crucial aspects, Mestry et al. (2011) propose an optimization model that leverages MILP techniques to efficiently solve the planning problem. Consequently, this study not only sheds light on the application of MILP models in the realm of production planning but also effectively addresses the typical characteristics encountered in industrial production scenarios. As a result, it fills a noteworthy gap in the existing literature by providing a comprehensive framework tailored to this specific context, thus offering valuable insights and practical contributions.

To conclude this topic, it is required to emphasize the significant findings from the studies discussed. It is worth noting that multiple studies have been carried out and applied across diverse industry sectors, highlighting the extensive research conducted on this subject. The research conducted by Jonsson and Ivert (2015) emphasizes the significance of the planning environment and process maturity in shaping the performance of the MPS. By examining the influence of these factors, the study provides valuable insights into optimizing the MPS. In a similar vein, the perspective defended by Vieira and Favaretto (2006) underscores the transformative role of computer systems in streamlining and enhancing production planning and scheduling, particularly when aiming for optimization objectives. Furthermore, the analysis carried out by Guzman et al. (2022) on the literature reveals a diverse range of models and approaches employed to address production planning, scheduling, and sequencing challenges, with a specific focus on real-world implementation using large-scale datasets. Drawing from these comprehensive studies, decision-makers can gain invaluable insights to refine their decision-making processes, enhance operational efficiency, and foster sustainable growth across various industrial domains.

3. The problem

This chapter is dedicated to introducing the problem addressed in this project, with the aim at providing an overview upon the case and the industrial environment. This chapter is segmented into four main sections: a problem description, an assessment of the planning context, a data overview considering an exploratory analysis, and an exposition of the key findings and challenges. Section 3.1. depicts a brief explanation of the problem at hand and emphasizes the opportunities for improvement identified in a previous diagnostic phase in the company. Section 3.2. outlines the company's planning context. Firstly, Section 3.2.1. presents a description of the production environment and process, followed by an overview of the company's current practices for medium-term planning in Section 3.2.2.. Section 3.3. encompasses a comprehensive examination of the available data, providing both an overview and an in-depth analysis, with the purpose to glean significant insights pertaining to the contextual aspects of the problem. Finally, Section 3.4. discusses the central discoveries and challenges derived from the study of the planning context, which rendered the problem highly intricate, necessitating a methodology capable of effectively managing this complexity.

3.1. Problem Description

Tactical production planning is a critical process as it helps companies plan their resources in the medium term. This process enables to forecast and allocate production volumes, workforce, and inventory levels for each period, in order to meet the varying demand. By having a clear understanding of the resources necessities, companies can better manage material requirements and capacity planning, and optimize their operations. As a result, they can reduce costs by avoiding stockouts and minimizing inventory holding costs, and improve customer satisfaction by meeting their demands more efficiently. Additionally, it enables companies to maintain their competitive advantage in the market by reducing their production costs and improving their efficiency. On account of this, it is essential to invest in tools that allow to develop and implement an effective production planning process.

Managing tactical production planning can be a challenging task for manufacturing companies since it involves several trade-offs. Firstly, the trade-off associated with the strategic decision of how much volume to produce. On one hand, increasing the production volume enables companies to meet customers' demands, but it can result in higher inventory levels. On the other hand, reducing the production volume minimizes inventory holding costs but increases the likelihood of stockouts and lost sales situations. Secondly, the trade-off between efficiency and setups costs – focusing on production efficiency maximization can result in higher setup costs and longer production lead times, while limiting setups might lead to less efficient resource usage. Following this line, optimization methods that are able to leverage the available data, deal with the production planning trade-offs in a holistic approach and yield an optimal outcome can provide major benefits nowadays.

As previously mentioned, a prior assessment conducted within the company had highlighted a number of areas for improvement. These improvement opportunities have a broad scope and encompass various departments, including demand planning, production planning, and procurement, and are regarded as holistic improvements for the company. Nevertheless, the ones related with production planning were deemed the most advantageous and thus the ones that this thesis focuses on. Specifically, the urgency lies in addressing the tactical production planning aspects, as they are considered to have the highest priority and potential for delivering significant value to the company in the future. Furthermore, the development and execution of a monitoring layer, available to the planning team reveals to be a complementary tool to the optimization model. This tool has the capability to offer additional data and information for the planning process, allowing for more informed decision-making, and planning process results quality monitoring and relevant KPIs tracking.

In this way, and drawing inspiration from the work of Meyr et al. (2000), Figure 7 was drawn up, depicting the project's scope – Master Production Scheduling and Capacity Planning – within the supply chain matrix. The MPS, which specifies what items to make when depending on the anticipated demand, is a crucial part of tactical production planning. It operates as a medium-term production activity plan and forms the foundation for material and capacity planning. Another key component of tactical production planning is capacity planning. It entails figuring out the resources required to satisfy the demand projection made in the master production schedule. As Figure 7 highlights, MPS and capacity planning have a bi-directional relationship with purchasing department, since medium-term production scheduling aids raw materials requirements planning and thus facilitating its availability when later required. Furthermore, the referred two functions of tactical production planning, directly affect operation scheduling, and ensures viable production plans at a short-term level.

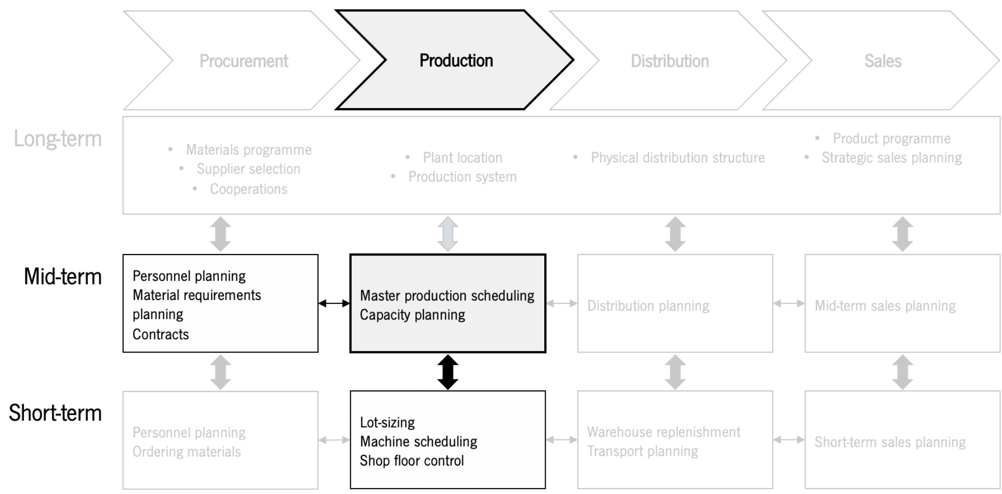

Figure 7: Project's scope. Source: Meyr et al. (2000) (adapted)

The analysis of the company's medium-term planning came to the conclusion that master production and tactical plans were not routinely created on the foundation of a global cost-service function. Instead, single constraint analysis was carried out in an *ad-hoc* and incomplete manner, failing to arrive at the lowest cost. Additionally, there was no anticipation of production orders, hence the MTO forecast was not accounted for, as reserved capacity, in the plans. Lastly, products were assigned to their corresponding preferred lines, even if it meant lower efficiency and a sub optimal solution. Due to these factors, it was challenging to plan production capacity with the anticipation required while managing and coordinating all the resources that would be engaged.

3.2. Planning Context

The company under study is a Portuguese filling company that specializes in contract manufacturing of a variety of products, including cosmetics, personal care, homecare, and pharmaceuticals. The company operates internationally, with facilities spread over five different countries. For the purpose of the project, the analysis considers only the production planning of two filling plants – designated by Factory 1 and Factory 2 – with a total of more than 20 production lines, contemplating both aerosols and liquids lines. Both factories are accountable for the production of more than 1000 products across more than 20 well-known customers.

Company's production planning includes long-term, medium-term, and short-time planning. Firstly, in the long-term planning, a yearly budget-based plan is established, and a six-month plan is developed to analyse how the projected production volumes will fluctuate over time and compare with actual production. The main focus is on tracking the evolution of the KPIs relevant to production. By adopting this strategy, the company can better understand the manufacturing process, pinpoint areas for improvement, and make the required adjustments to maximize productivity and efficiency. Additionally, company can ensure that they are meeting their targets and delivering high-quality products to their customers by closely and constantly monitoring the production KPIs.

Secondly, in the medium-term, a monthly perspective is adopted to evaluate the weekly planning for the current and upcoming three months. This involves assessing fixed, binding, and forecasted orders to determine the allocation of line capacity based on projected volumes. To gain a better understanding of the process, it is important to clarify the concepts associated with the three distinct periods: fixed, binding, and forecast. The fixed period entails a commitment to producing a specific quantity of finished products per week. In contrast, the binding period extends this commitment to encompass the total quantities of materials required for the designated period. The forecast period does not impose an obligation to procure predetermined quantities, thereby providing greater flexibility in making purchasing decisions. Given the examined context, tactical planning emerges as a critical role in fostering cohesion among diverse company departments and ensuring the seamless execution of short-term production objectives. Consequently, owing to its profound significance, it assumes a central role and becomes the primary focal point of the project. This strategic emphasis on tactical planning reflects its pivotal role in facilitating interdepartmental coordination, optimizing resource allocation, enabling the timely fulfillment of production targets, and providing valuable insights for decision-making processes.

Lastly, short-term is based on weekly plans, with order allocation per line, providing the basis for production scheduling. The short-term planning considers the availability of raw materials, expected line capacity, and workforce availability. If necessary, the short-term planning suggests postponing production or working in overtime to meet production demands and targets. Daily scheduling is then built, considering setup reduction, workforce levelling and accommodating blending capacity constraints. Making the best use of the resources at hand is the primary goal of short-term planning in order to guarantee that the daily production schedule is met.

Regarding the company's planning context, although tactical planning is similar between both production sites under study (Factory 1 and Factory 2), synergies between both sites are currently not accounted for. Tactical production planning is made independently, based on their expected customer orders and availability. Nonetheless, the company's planning context is still very complex, with multiple dimensions to be considered. Some of those features of the planning context are listed below.

- Since customers place orders well in advance, the majority of products see considerable fluctuations in demand. This means that over time, the level of interest and desire for a product might fluctuate quickly and in an unpredictable manner, making it difficult to foresee and efficiently handle consumer demand.
- The number of available items has increased as a result of the market's desire for a wide range of finished goods. This proliferation of product options can be attributed to pressure from consumers who are seeking more personalized and unique products that meet their specific needs and preferences.
- The production plan follows a MTO approach, meaning that each production order is linked to a specific customer order, without producing for non-allocated stock. In this way, company ensures that production aligns with the actual customer demand, avoiding excess inventory. However, is feasible to anticipate part of the binding and forecasted orders. Despite not having excessive inventory, there are some additional challenges related to the topic. For instance, the planning is susceptible to demand volatility, there is limited capacity for consolidating productions and ensuring efficiency, and there is a greater need for effectively connecting processes to ensure the availability of raw materials for each individual case.
- Production plan is aggregated at a monthly level to support capacity and shift planning and to more effectively allocate resources and plan for necessary adjustments. This plan involves determining the expected usage of each production line, the planned production of each Stock Keeping Unit (SKU), and the requirements for work schedules and shift.

- Various technologies are utilized in each stage of the production process, which implies that various methods and instruments are employed for various stages.
- Each production line requires a specific crew of workers to run, and the number of workers needed may vary depending on the line being used. This means that the company needs to carefully evaluate the workforce necessary for each production line and ensure that they have the right number of workers with the appropriate skills to manage the operations efficiently.
- Must be considered sequence-dependent setup times, meaning that the time required to prepare for a specific product run may vary depending on which product was produced immediately prior to it.
- To manufacture a production batch, a particular set of raw materials, which can be either in-house or arriving until the production week, are required according to the BOM. Nevertheless, specific finished goods have alternative BOMs, allowing them to be produced using different combinations of raw materials - recipes -, depending on their availability at the time of production. As a result, a production batch is only slotted into a given week if raw materials are expected to be available at a given production date. In other words, to ensure that each batch can be produced effectively and without any delays, the production scheduling procedure takes the availability of raw materials into account.
- Different raw materials are provided by distinct suppliers with different lead times. This feature demands for accurate and up-to-date information on lead times to reduce the risk of delays and production downtimes due to material shortages.

The production planning context of the company under study can be categorized based on the six crucial decisions necessary for ensuring coherence and effectiveness throughout the production process, which are presented in Thomas and McClain (1993) and previously mentioned in Section 2.2..

1. **The time unit:** production plan based on a weekly time frame, where the production orders for a given week will be assigned to the respective production lines. This approach allows for a more granular and manageable planning process that helps to streamline the production process and ensure timely delivery of products.
2. **The time horizon:** the production planning process encompasses a time horizon of 17 consecutive and rolling weeks, enabling greater flexibility in adapting to changes in demand, production capacity, and raw material availability, and to stay agile and responsive to any unforeseen circumstances that may arise.
3. **Level of aggregation of the products:** the products in the production planning process are analysed in full detail, ensuring that the level of aggregation is precise and comprehensive. This approach is necessary to accurately evaluate and understand the associated costs to each product, including raw material and labour.

4. **Level of aggregation of the production resources:** the production resources in the company are aggregated according to the production line they are associated with. There are no significative discrepancies observed between the different types of machinery within one line and the workers who operate the different lines, in terms of their abilities and competencies. Thus, each production line has its own unique characteristics, including measures like the OEE and throughput. Additionally, each product can only be manufactured on designated lines, in accordance with predefined routing specifications.
5. **Frequency of replanning:** the company generate its production plans on a weekly basis, allowing for a detailed and dynamic view of the demand and production capacity for the upcoming weeks, as well as the ability to promptly change them as necessary.
6. **Number and structure of production plans:** currently, the company develop four types of production planning that vary in their time horizon and different time unit: long-term planning, monthly planning, weekly planning, and scheduling planning. The project under consideration pertains to the weekly planning process, which will be aggregated into a monthly plan. Figure 8 illustrates the four production planning types generated by the company, highlighting the scope of the project, and providing a summarized overview of each planning process.

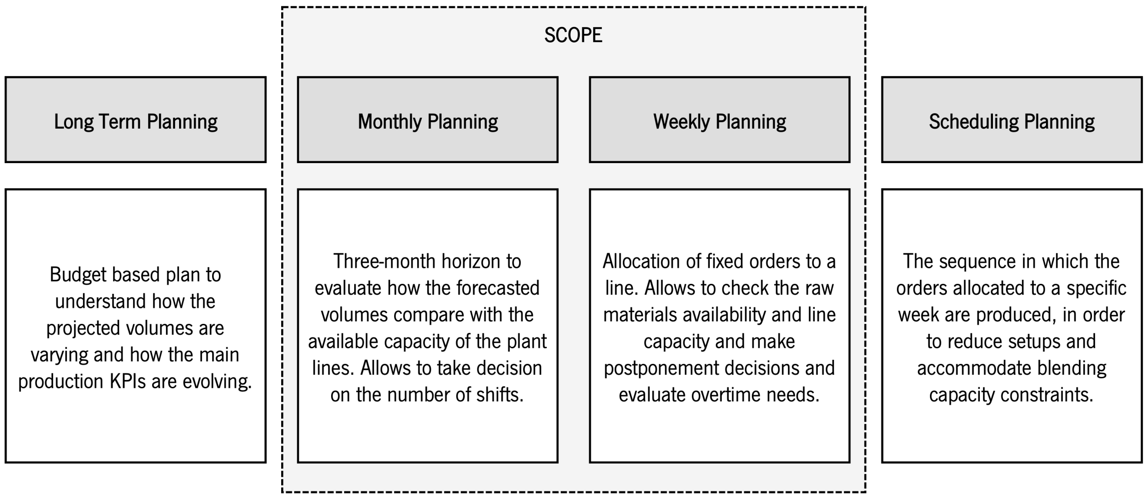

Figure 8: Number and structure of production plans

3.2.1. Production Environment and Process

The production environment and process of both plants was extensively mapped out, focusing on both aerosols and liquids businesses. The mapping aimed to identify material flows between the main stages of production for each SKU. The process study revealed that both plants have two main phases for each SKU production: blending and filling. However, there are also small and specific production phases for a set of SKUs that precede or follow the filling phase. These additional production phases include in-house assembly of components, such as glued trays in Factory 1 and special valves in Factory 2, or co-packaging, currently only in Factory 2. The process and environment mapping provided valuable insights into the complexities of the production process of both plants.

Nevertheless, it is crucial to clarify that the project's scope is limited to the filling operations, excluding blending operations and auxiliary processes. This decision is based on the understanding that filling operations are the most critical and central components of the overall production process. Furthermore, an extensive examination and evaluation of the production process revealed that the filling operation emerges as the bottleneck within the overall process. As a result, it presents the greatest opportunity for extracting value through the implementation of proposed enhancements. Within the framework of Factory 2, it becomes imperative to incorporate a supplementary stage and production line - Copacking line. This imperative arises from the prevalence of a multitude of products that necessitate undergoing a co-packing procedure. This procedural requirement entails the need for distinctive handling and meticulous adherence to designated time parameters during the production process.

All customer orders are translated into production batches. For each batch, the blending team starts by weighing all important raw materials according to a recipe, before mixing them inside one of the client-approved reactors. The final mix can be stored in fixed or movable containers, according to the blend necessities and availability, for a certain amount of time. This team must also account for the blending time and resting time of certain materials and mixes, so that the blend (bulk) is ready when the filling team needs it. After the blending phase, the mixture can be used in one or multiple lines according to the production schedule and routings. The filling operation is a set of sequenced activities, such as: filling each can with the specific blend, inserting the valve, pressurizing the can, weighting, applying a hot bath, checking particle leakage, checking the code, and packing operations. At last, the finished goods are moved to the warehouse where they are stored until the client picks them up. This process for each factory, in particular, is detailed in the upcoming sections.

3.2.1.1. Factory 1

Factory 1 is the largest plant within the project's scope. It possesses 8 production lines dedicated to aerosol and 8 dedicated to liquids. Due to its size, it produces large orders and is mostly at full capacity regularly. It encompasses hundreds of workers, of which some of them are temporary workers. Generally, the working schedule for this site is five days a week, with operations running 24 hours a day. However, in order to meet high volumes of production demands, the factory has the ability to increase capacity in the short-term by adding additional shifts and overtime hours on the weekends. By doing so, the plant can extend its working schedule to a maximum of 24 hours a day, seven days a week, provided that such an extension is planned at least one month in advance. Given this flexibility and adaptability, the site can meet production targets and quickly adjust to changes in demand.

The production volumes at this plant are considerably high, and as a result, the blending operation can have a significant impact on the subsequent operation – the filling operation. This happens because some products require special reactors where to be produced or stored, since customers only approve some reactors. Despite that, the production planning team is aware of these constraints and takes them into account during the scheduling planning, where the best sequence of production orders is determined, in order to mitigate such limitations and ensure that the production process runs smoothly and efficiently.

Furthermore, it is noteworthy that some products, mostly liquids, due to their characteristics, need to undergo the quarantine phase for longer periods. Consequently, in order to ensure timely delivery on the agreed-upon date, the finished goods' production must start with enough advance time. Furthermore, there are specific regulations that restricts the amount of dangerous and explosive goods that can be stored, which affects the storage capacity for aerosol products.

The production process described is illustrated in Figure 9, presented below.

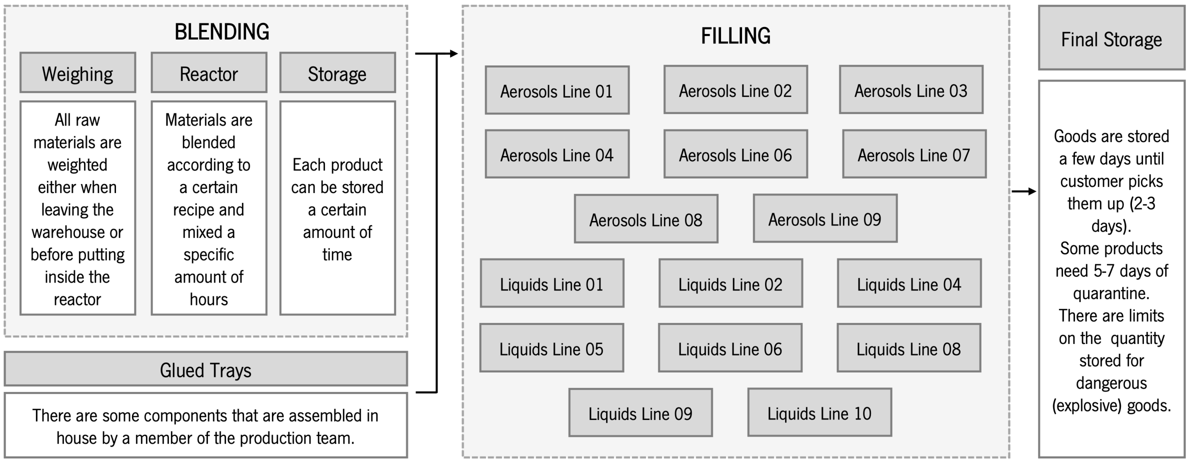

Figure 9: Production process of Factory 1

3.2.1.2. Factory 2

Factory 2 is a smaller facility, when comparing with the dimension of Factory 1, with a total of 8 filling lines: 6 lines dedicated to aerosols, with 5 for cosmetics and 1 for non-cosmetics, 2 lines dedicated to liquids, and 1 line dedicated to the co-packing process. However, to enhance simplicity and comprehensibility, the Copacking line is regarded, within the context of this document, as a filling line. Currently, Factory 2 functions without temporary workers, although, if necessary, hiring them is a possibility. Production volumes are generally lower than those of the larger plant, meaning that the site usually operates in a working scheduling of 16 hours a day over five days. In case of short-notice capacity increase, the factory can add two extra working hours per day, by implementing a working schedule of 18 hours/5 days. Additionally, and similarly to Factory 1, it is possible to increase capacity by opening two additional shifts on weekend or, with prior notice of one month, moving to a 24 hours/5 days or 24 hours/7 days working regime. Undertime is a viable scenario in Factory 2, which allows capacity reduction by a shift or a full day. However, this may require payment of fixed labour hours due to the high prevalence of permanent workers.

In terms of the production process, Factory 2 has a similar layout to Factory 1, with two main phases for each SKU production – blending and filling –, and the blending phase is carried out in the same way for both aerosols and liquids. When examining the production specificities of the Factory 2, there are some important aspects to keep in mind. Due to the smaller volumes, blending operations typically do not present a significant bottleneck for the filling operation team. Furthermore, this plant produces some SKUs that require specific valves assembled in-house, which means that the planner must consider the reduced manpower for the filling team, as a result of the required allocation of one member of the filling team to assemble valves in the weeks when those SKUs are produced. Since this member is removed from the production team, it is important to group the production orders that require this component in the same week, to minimize the generated entropy and minimize disruptions to the global production process. Finally, some SKUs require to be co-packed, which entails that the planner should plan both SKUs in the same week to minimize the need to store one of the products while waiting to produce the other. This aspect requires close coordination and planning by the production team to ensure that both SKUs are produced on schedule and without any delays. Overall, Factory 2 is a smaller facility than Factory 1, but it still plays an important role in the company's production operations. The flexibility to adjust working hours and capacity levels allows for efficient use of resources and ensures that production can meet customer demand.

Figure 10 clarify the production process implied in the Factory 2.

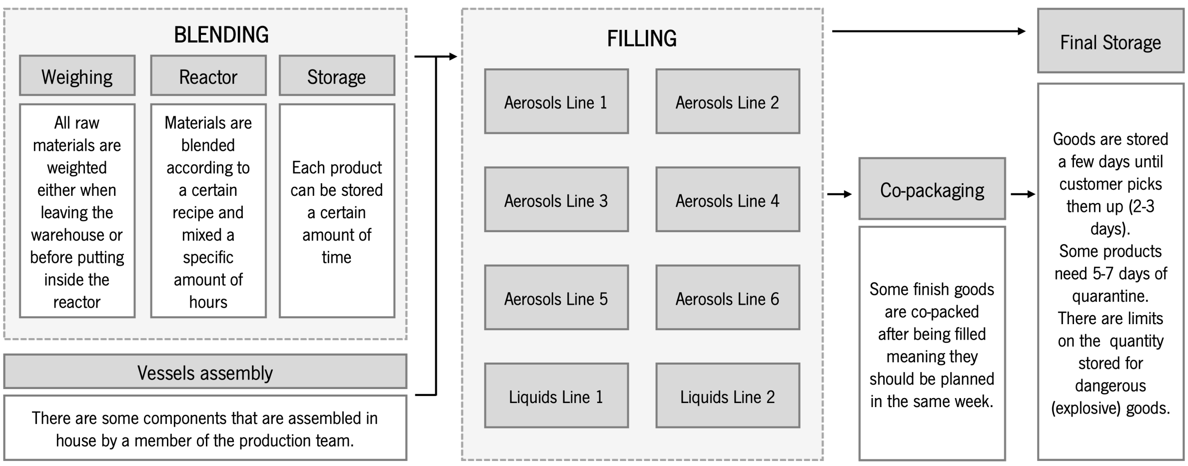

Figure 10: Production process of Factory 2

3.2.2. Current Practices

Presently, the company's production planning is a non-standardized and non-automated process, and it is carried out on an *ad-hoc* basis. Furthermore, the production planning process is carried out individually for each customer, with distinct team members assigned to handle the planning for each customer. This suggests that there is no clear or consistent framework or set of procedures in place for planning and managing production. Instead, the process relies heavily on the experience and expertise of individual team member responsible for planning. In addition, the processes of production smoothing and order pooling are performed manually with support of spreadsheets. Consequently, the production planning procedure could be ineffective, highly repetitive and time consuming, prone to errors, and vulnerable to delays or disruptions brought on by unforeseen events.

The production planning processes currently followed in the company were mapped in order to gain a clear understanding of the various procedures involved and the rationale behind the decisions made. Each step in the production planning process was exhaustively analysed, enabling the identification of specific tasks, areas of improvement, timelines, and decision points. Additionally, this mapping process allowed for a better understanding of the factors that are driving the production process decisions and enabled the optimization of the planning process accordingly.

The process of generating the weekly plan begins with the receipt of forecasted orders for fixed, binding, and forecast period, from the customer service team. Is important to remember that during the fixed period, the quantities represent a commitment of finished products per week. During the binding period, the commitment is for the total quantities of materials for that period. However, in the remaining period – forecast period –, there is no obligation to purchase the agreed-upon quantities. The aim of this process is to assign orders to a particular filling line schedule while maximizing flexibility wherever feasible.

Each manufactured product has a MOQ requirement associated with it. Moreover, certain products belong to a specific family characterized by similar attributes, thereby imposing a MPR that must be adhered to. In the company under study, the MPR entails the minimum quantity of a product that a manufacturer is willing to produce in a single production run. Therefore, the cumulative production of products belonging to the same family must align with the predetermined MPR quantity established for that particular family.

In this way, once the forecasted orders are received, they are carefully reviewed to ensure that they comply with the MOQ and batch size constraints. If any discrepancies or non-compliances are detected, they are promptly communicated to the customer service team for resolution. Subsequently, for the products that belongs to the same family, the planning team reviews the forecasted orders to ensure that they comply with the MPR constraints. These steps are critical to ensuring that the production process goes without any difficulties and that orders are appropriately and effectively fulfilled.

Once all orders have been settled, the availability of critical materials is checked to guarantee that all production orders can be fulfilled and assigned to the preferred or priority line. If the line capacity is exceeded, the planning team rearranges the orders to address overcapacity issues. In cases where reassignment is not possible, the orders are placed in a "backlog queue" – waiting line in which an order sits waiting to be produced in case of other orders being delayed, due to lack of raw materials or lines running faster than expected.

After the production plan has been finalized, it is forwarded to the purchasing team to verify the requirements for raw materials and to the customer service team to confirm the planned orders. This ensures that the necessary materials are available and that customer orders are fulfilled according to the plan.

Figure 11, which shows the flowchart of the weekly production planning, was developed with the purpose of visually representing the sequence of steps that make up the production planning process previously described.

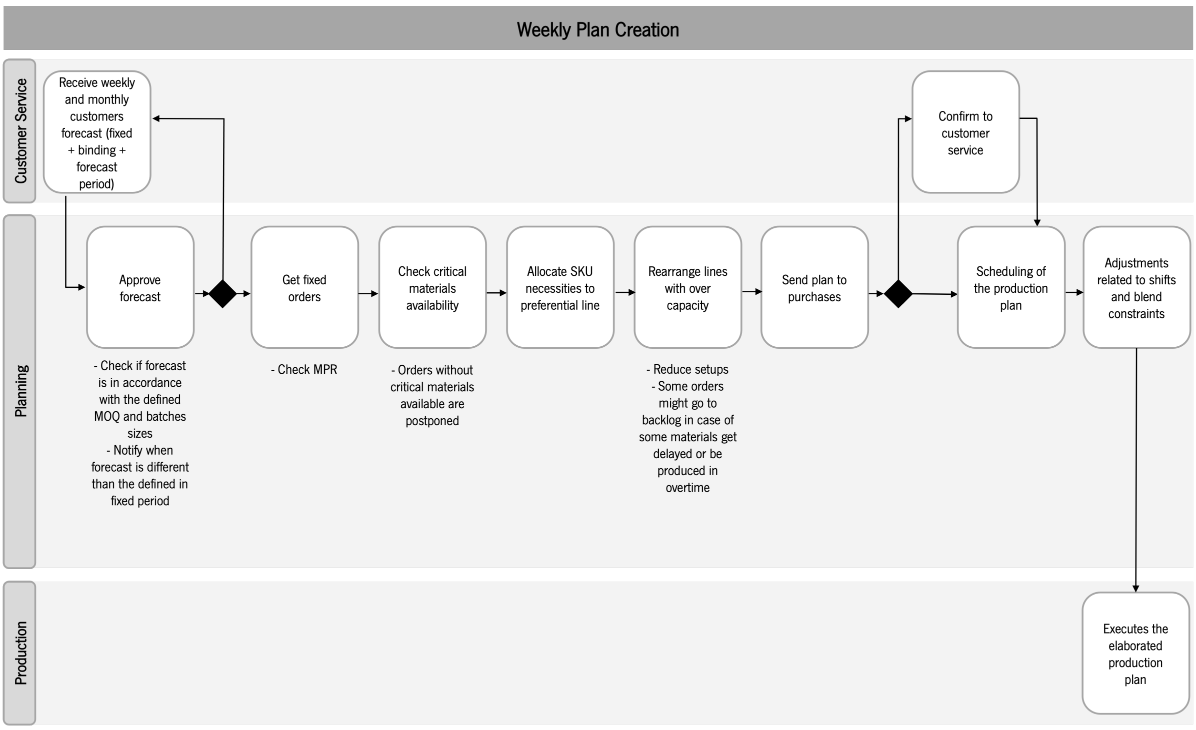

Figure 11: Weekly production planning flowchart

3.3. Data Overview and Exploratory Analysis

Having navigated through the intricacies of the problem description, contextual understanding, and an analysis of current practices, the imperative now lies in according proper significance to the available data. Delving into the realm of data overview and conducting an exploratory analysis hold significant importance, enabling to address pertinent challenges and examine the behaviors exhibited by various variables. This pivotal chapter marks the transition from theoretical groundwork to practical insights.

Data outline

Initially, and preceding the actual exploratory analysis, it is imperative to delineate certain overarching data regarding the problem under study. The problem being investigated encompasses two manufacturing facilities located in distinct countries. The first facility - Factory 1 - is engaged in the production of a diverse array of 1844 products, allocated among 32 customers. The production of said items requires the utilization of 5338 discrete components. Manufacturing operations at the Factory 1 encompass 16 filling lines, 8 of which are dedicated to aerosol production and 8 to liquid production. The second facility - Factory 2 -, of lesser scale, is tasked with the manufacture of 645 distinct products pertaining to 32 clients. The production of these items is executed employing 2498 varied components, each characterized by unique attributes and functionalities. The second facility comprises a total of 8 filling lines, with 6 dedicated to aerosols and 2 to liquids. The aforementioned data are meticulously depicted within Table 2 provided below.

Table 2: Problem's data outline

	Factory 1	**Factory 2**
Products	1844	645
Customers	32	32
Raw Materials	5338	2498
Filling Lines	16 (8 Aerosols Lines + 8 Liquids Lines)	8 (6 Aerosols Lines + 2 Liquids Lines)

Demand profile analysis

Afterwards, an analysis utilizing the ABC-SEL methodology was executed on finished products, incorporating both the sales percentage and the proportion of products allocated within each category. This assessment classifies the products into distinct categories of A, B, and C based on their relative significance regarding sales. Products A represent high-value items, constituting a smaller portion of the total inventory but accounting for a large share of sales. In contrast, items in category C are labeled as low-value, as they are typically abundant and have a lower impact on revenue (Scholz-Reiter et al., 2012). Moreover, it refines this analysis into classifications of stable, erratic, and lumpy demand. This stratification aims to facilitate an in-depth examination of the demand characteristics of each product. The differentiation into stable, erratic, and lumpy designations takes into account the demand variability and the degree of intermittency exhibited by the products. The variability is calculated based on the variation of the quantities sold, while intermittency is calculated by the average interval between sales. In this context, a stable product is characterized by minimal variability and intermittent behavior in its demand patterns ($variability \leq 0.49$ and $intermittency \leq 1.32$). Thus, should be the ones where forecasting accuracy is expected to be better. Conversely, an erratic product showcases pronounced variability while demonstrating limited instances of intermittency ($variability > 0.49$ and $intermittency \leq 1.32$). Lastly, a lumpy product demonstrates pronounced variable and intermittent demand patterns ($variability > 0.49$ and $intermittency > 1.32$) (Boylan et al., 2005).

In the context of the study, the analysis involves considering, for each product of Factory 2, the estimated forecast, for a period of one month, and comparing it with the actual quantity sold, along with the intervals between customer demands. By incorporating the classification system proposed by Boylan et al. (2005), it was possible to categorize the items based on their variability and intermittency. The ABC-SEIL analysis mentioned earlier is visually represented in Figure 12.

% Sales (%) % Products (%)

		A	B	C	
Stable	Sales	22,0%	0,0%	0,0%	22,0%
	Products	4,4%	0,0%	0,0%	4,4%
Erratic	Sales	22,4%	0,5%	0,0%	22,9%
	Products	7,6%	1,0%	0,0%	8,6%
Lumpy	Sales	35,6%	14,5%	5,0%	55,1%
	Products	23,0%	29,2%	34,8%	87,0%
	Sales	80,0%	15,0%	5,0%	
	Products	35,0%	30,2%	34,8%	

Figure 12: ABC-SEIL demand profile analysis

Upon reviewing the ABC-SEIL matrix, it is apparent that just under 5% of the products are stable, illustrating the pronounced volatility in demand patterns. Furthermore, around 88% of the products classified as A fall within the erratic and lumpy sectors, emphasizing the necessity for precise data inputs when defining the strategy. Finally, the substantial cluster of products in the C-lumpy quadrant mandates agile adjustments in production lines to facilitate the creation of limited-scale batches. In summary, the significant variability and intermittent nature of sales underscore, from one side, the MTO nature of this business, but also the importance of agility in decision making.

Forecast variability and accuracy analysis

Once analyzed and highlighted the demand profile and its high vulnerability, it is important to gain insights into how demand predictions behave. Thus, an examination of forecast data was undertaken. Firstly, the forecast accuracy was assessed over a 17-week period, by applying the Equation (1).

$$Accuracy = \frac{\sum_{predictions} |ForecastQty - OrderQty|}{\sum_{predictions} OrderQty} \tag{1}$$

Figure 13 illustrates the accuracy for each factory, obtained by aggregating the values derived from Equation (1) for each specific factory. The curve clearly demonstrates a decline over time, significantly impacting the anticipation and aggregation of orders. It is important to mention that for the majority of customers, the fixed period is at least 3 weeks, making the forecasts for this duration highly reliable. However, beyond this period, there is a noticeable decrease in the accuracy of predictions.

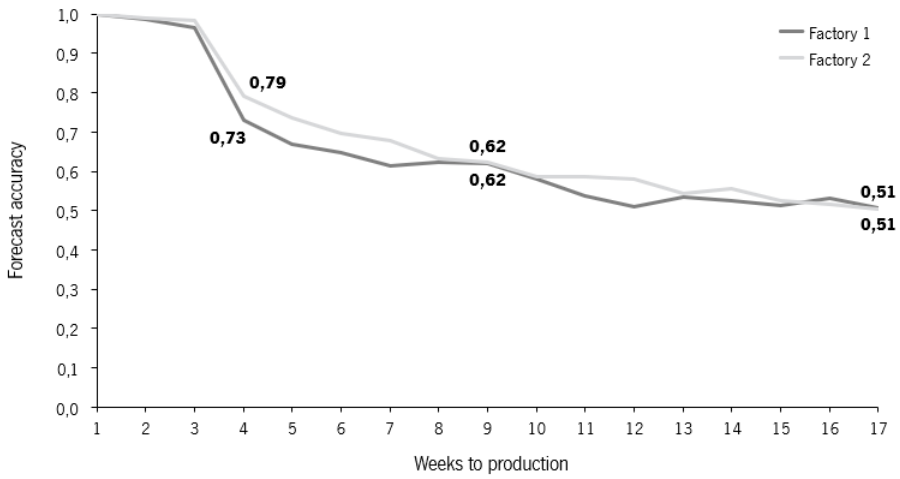

Figure 13: Forecast accuracy curve over 17 weeks

Secondly, the forecasts were evaluated based on the shortest time span where the ordered quantity is an estimate. This facilitated an analysis of forecast accuracy during the initial week when the ordered quantity is yet to be confirmed. For instance, if a client had their ordered quantities confirmed for the next 3 weeks, the forecast accuracy was scrutinized for the 4th week. These evaluations were then compared to the actual quantity ordered by the customer.

Estimating the forecast accuracy revealed noticeable differences in forecast accuracy among different customers. These variations highlight the varying levels of risk faced by the company when relying on forecasts during the binding period. Moreover, it was possible to classify eight clients into three distinct categories in accordance to the level of reliability translated by the percentage of accuracy associated to the forecast - reliable ($accuracy > 95\%$), moderately reliable ($80\% < accuracy \leq 95\%$), and unreliable ($accuracy \leq 80\%$). This classification is visually represented in Figure 14.

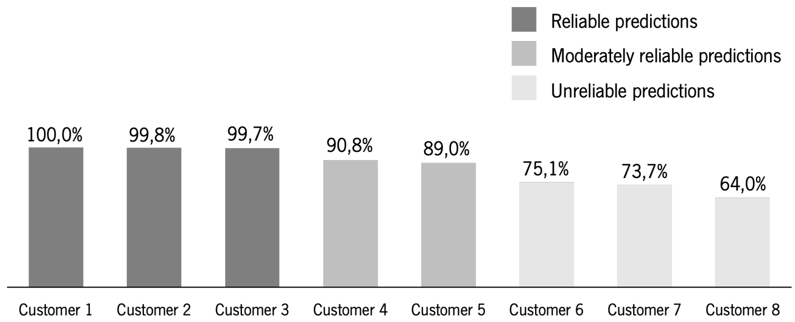

Figure 14: Forecast accuracy for different customers

Another aspect to carefully examine when evaluating the accuracy of the forecast is the bias linked to it. Bias denotes a systematic and persistent deviation from the true value, thus constituting a valuable metric. For the present study, the error was calculated considering a granularity of material, week of the year and difference between the date of the forecast and the order date. These errors were then aggregated for each client by summing the absolute errors and dividing them by the total quantity ordered. Therefore, the bias, quantified as a percentage, can be ascertained through the application of the provided formula.

$$Bias = \frac{\sum_{predictions}(ForecastQty - OrderQty)}{\sum_{predictions} OrderQty} \tag{2}$$

The chart illustrated in Figure 15 encompasses the percentage value of bias for each customer, whose forecast variability was examined. It is imperative to emphasize that the customer identification in this graphical representation corresponds to the designation provided in the Figure 14.

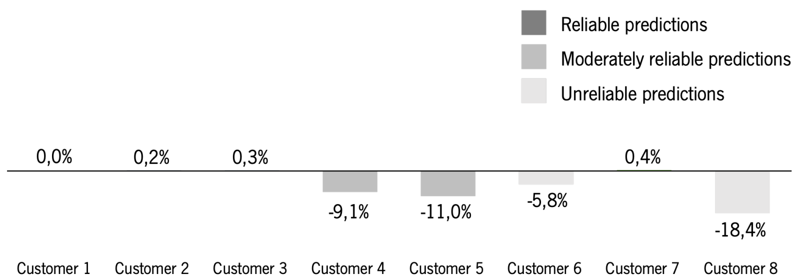

Figure 15: Forecast systematic bias

By examining the graph, is possible to emphasize that customers with higher forecast accuracy exhibit positive and residual bias values, below 0.5%. Additionally, among the total of the eight clients analysed, four clients showcase a negative bias with a substantial percentage value. In the context under study, it can be inferred that these clients place orders exceeding the quantities forecasted, with the client exhibiting the poorest accuracy also holding the most significant negative bias value.

Synthesizing the data from both graphs underscores the existence of notable disparities in customers' forecast reliability, leading to varying levels of risk, where customers with less reliable forecasts necessitate closer monitoring. Consequently, there is a need to devise a strategy for mitigating forecast-associated risks, employing a methodology equipped to handle this challenge.

Product allocation across filling lines analysis

Several exploratory data analyses were conducted to track the extent of the issue and identify the major challenges inherent in the case under examination. Firstly, the distribution of products across various filling lines in each of the factories was investigated. This distribution is depicted in the graphs of Figure 16, which detail the percentage of total products allocated and produced on each filling line in both Factory 1 (top graph) and Factory 2 (bottom graph). It is of importance that, in this analysis, products with production routings for multiple filling lines are considered in all the filling lines where they can be made.

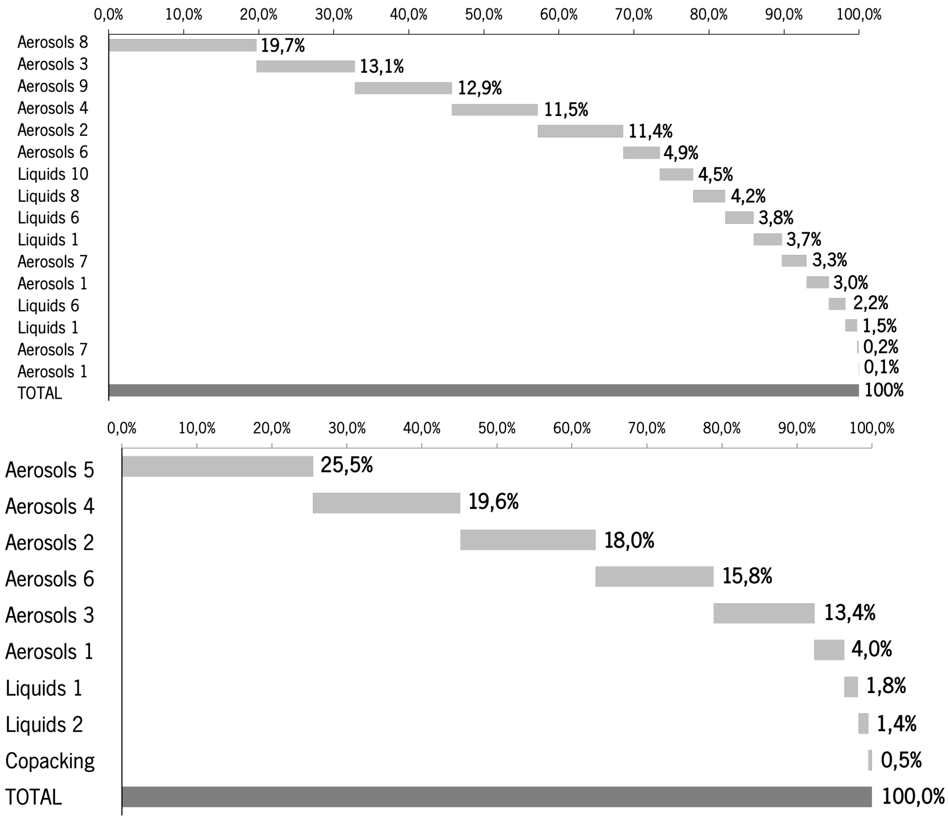

Figure 16: Product allocation across filling lines

Through the analysis of the graphs, it's evident that in both factories, there is a disparate distribution of products across the lines. Some filling lines are utilized for a significant percentage of products, while others are specialized in products with specific characteristics and are occupied by a much smaller percentage of items. Additionally, a dominance of aerosol lines (LA) over liquid lines (LL) is noted, with aerosol lines being occupied by a higher percentage of products compared to liquid lines.

Turning attention to the graph related to Factory 1, it becomes apparent that filling lines LA02, LA03, LA04, LA08, and LA09 collectively account for producing 68.6% of the total products. In contrast, LA01 is employed for a limited number of products, constituting only 0.1% of the total. As for Factory 2, line A5 emerges as the predominant filling line, being employed by the largest proportion of products, totaling 25.5% of the overall product count.

The fact that products are unevenly and unbalanced distributed across the lines poses a challenge to the problem, as it necessitates a more careful allocation of products to each line. Moreover, it involves a more considered decision-making process for the working schedule, which needs to be tailored to the unique characteristics of each of the filling lines under study.

SKUs produced across multiple filling lines analysis

Following that, an array of analyses was conducted on the data, exploring different elements such as filling lines, SKUs, and components. The main goal was to understand how certain products could be manufactured using multiple production lines and to unravel the complex relationships between products by examining the shared use of components in their formulations.

This scrutiny carries significant weight due to the existence of several production possibilities for products and the intricate interplay of components across different items. This complexity demands a sophisticated optimization model capable of assessing each unique scenario and making informed decisions to maximize the company's benefits. Such an approach is pivotal in navigating the intricate landscape of production optimization, ensuring that the most advantageous choices are made considering the multifaceted relationships within the product ecosystem.

Taking the aforementioned points into consideration, the analysis depicted in Figure 17 was developed with the intention of identifying the instances where products have the option of being produced using more than one filling line.

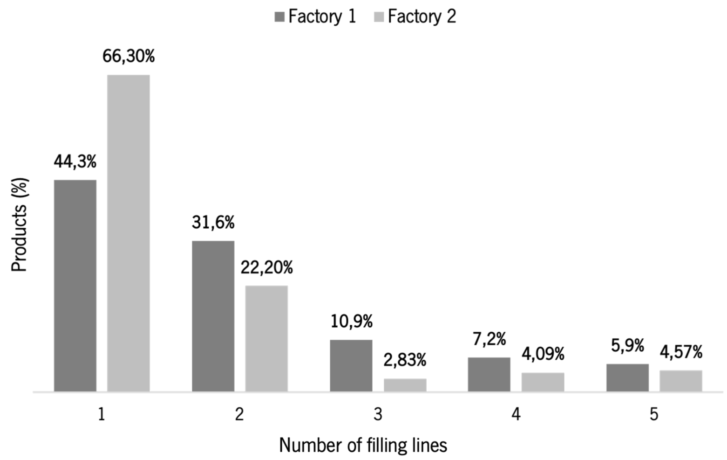

Figure 17: Skus produced across multiple filling lines

Upon examining Figure 17, it is discernible that a considerable number of products possess multiple filling line alternatives within their production routings. Notably, the largest segment of products can be manufactured using just one filling line in both Factory 1 and Factory 2. Concerning Factory 2, the majority of products, accounting for about 66.3%, are constrained to production in a single filling line. Nevertheless, a smaller proportion of products, constituting 5.9% in Factory 1 and 4.6% in Factory 2, can be produced using five filling lines. This presents a major challenge and complexity for the model. In the given scenario, when a product can be made on five different lines, the optimizer has to evaluate five production options, taking into account the cost and speed of each line. Additionally, opting for one line over another can result in significant alterations to other products and the overall production planning.

SKUs with alternative recipes analysis

Another factor that further amplifies the dimension of the issue is the number of recipes each product possesses. As mentioned earlier, certain products can be manufactured using more than one set of alternative components, referred to as BOM recipes. The presence of multiple recipes necessitates monetary and logistical analysis for each alternative, considering the implications that each decision entails. This is because producing a product with a specific recipe might result in the non-production of another product that also involves the same components. Figure 18 contains a histogram that highlights the percentage of products in each of the factories that have more than one recipe.

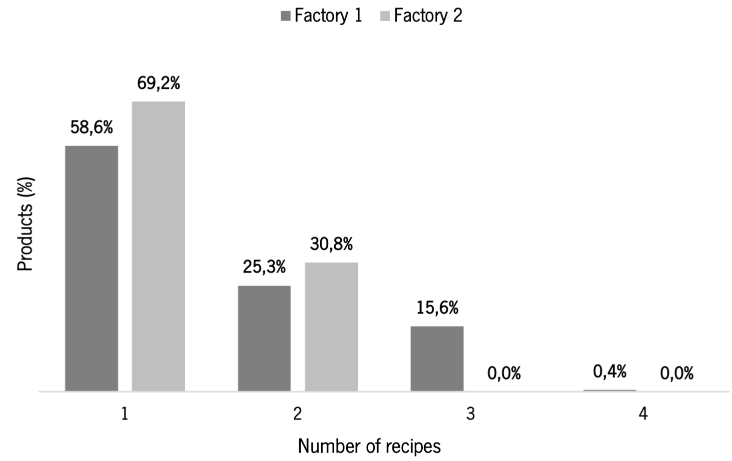

Figure 18: Skus with alternative recipes

After closely examining the graph, it becomes clear that most products in both factories have only one recipe. This is particularly evident as 58.6% of products within Factory 1 and 69.2% within Factory 2 can be exclusively produced using a singular recipe. Nevertheless, a substantial proportion of products exhibit a diversity of recipe alternatives. It is pertinent to draw attention to the fact that Factory 1 showcases a unique scenario, wherein 0.4% of its products accommodates the flexibility of employing four distinct component recipes. In contrast, the landscape in Factory 2 is characterized by a distinct boundary, where products are constrained to a maximum of two recipes. This variance in recipe options in the two factories underscores the complexity involved in production planning and the intricate web of decisions that must be navigated to optimize production efficiency and resource allocation.

Regarding the BOM recipes, it is key to highlight that Factory 1 employs 13 different components for each BOM recipe, whereas Factory 2 uses an average of 12 distinct components. This evidence the necessity of having all these unique parts accessible when manufacturing a specific product. In essence, the smooth creation of the item heavily relies on ensuring that all elements are available at the exact production moment. This level of component readiness amplifies the intricacy of the challenge as multiple prerequisites must align to enable the production of a single item.

SKUs with shared raw materials analysis

The last analysis sought to determine the proportion of all products that utilize common components among other finished goods, emphasizing the count of shared components. Given that multiple products share identical components, it becomes essential that, in cases where component stock limitations hinder the production of all finished goods, the model must be capable of effectively prioritize a set of products that would offer the highest benefit to the company. This entails optimizing the production plan for maximum suitability and profitability. As a result, the histogram shown in Figure 19 was constructed to encompass this data for both factories under study.

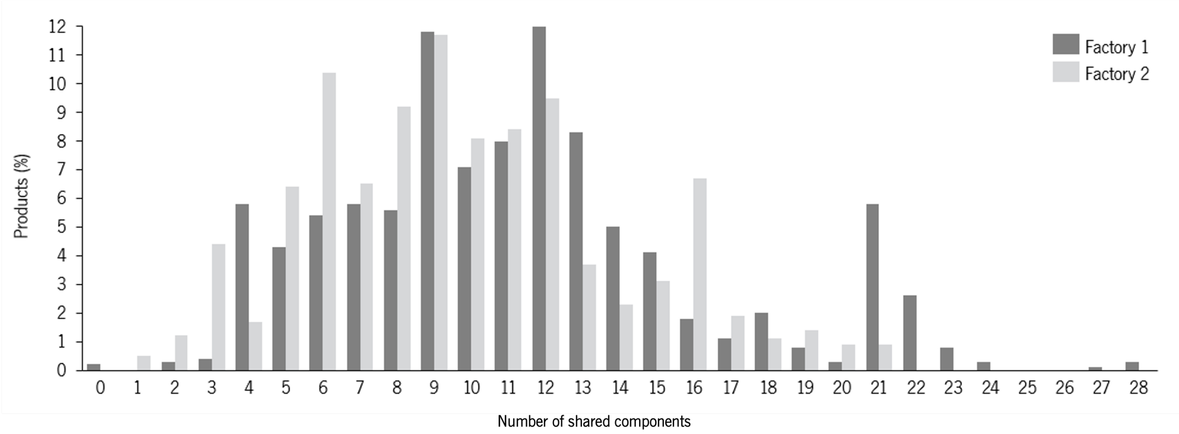

Figure 19: Skus with shared raw materials

Analyzing the graph, it becomes evident that the vast majority of products in both factories do not possess unique BOM recipes, as they share at least one component with other products. In Factory 2 all products share components with other products, where in Factory 1, only 0.2% have unique BOM recipes. Furthermore, it was observed that some products share nearly all of their components with other products, and this phenomenon is particularly notable among products within the same product family. As a result, the model faces a trade-off, given that the production of these products must align with the MPR. However, this production is constrained by the existing component stock, which must be sufficient for manufacturing products within the same family.

Concluding this section, through the execution of these exploratory analyses, it becomes feasible to highlight the complex nature inherent to the problem. The challenge stems from the gradual decline in accuracy experienced by each factory over the weeks, making it highly challenging to accurately plan orders that are not yet confirmed in the long term. The landscape is further complicated by the presence of numerous SKUs that possess the potential to be manufactured across multiple filling lines. Additionally, several SKUs exhibit multiple BOM recipes and share components with several other SKUs, thereby underscoring the intricate interplay of variables within the manufacturing process. All these aspects require the development of a highly robust optimization model capable of assessing and evaluating all conceivable decisions.

3.4. Key Findings and Challenges

Throughout the evaluation conducted on the planning process and current practices adopted in the company, and through the exploratory analysis carried out, important discoveries and difficulties emerged within the project's scope. The primary aim of the research was to devise a methodology capable of effectively tackling the identified factors within this particular context. However, it is to recognize that these factors have posed significant challenges, demanding the application of a complex, intricate and exhaustive methodology.

This chapter presents a comprehensive exploration of the key findings that have shaped our understanding of the process and planning environment, alongside the challenges that have impacted the development of the proposed approach. The complexities and challenges encountered are outlined below:

- The existence of substantial forecast uncertainty gives rise to an inherently volatile plan, presenting significant challenges in effectively coordinating raw material planning and optimizing the production schedule. The inability to accurately predict forthcoming demand patterns makes it arduous to ascertain the precise quantities of raw materials required at specific intervals. Furthermore, the absence of a dependable forecast further complicates the optimization of the production schedule, as aligning production activities with fluctuating demand becomes increasingly intricate.
- Factory's 1 demand often requires full capacity, even exceeding it at times, posing challenges that requires thoughtful decision-making. In this scenario, there is a need to carefully consider the trade-offs between two options: increasing the capacity with overtime schedules to accommodate the demand, which may result in additional operational costs and resource allocation, or opting to delay certain orders to align with the available capacity, which may incur penalties for late delivery.
- Factory 2 is currently experiencing lower demand compared to its production capacity, offering the potential advantage of optimizing cost savings through the closure of shifts and production lines.
- The filling lines are required to conform to the same working schedule for a duration of four consecutive weeks, thereby limiting the flexibility of the optimization methodology.
- A single product has the capability to be manufactured across multiple lines, each exhibiting distinct throughput and setup time characteristics.
- Products are required to adhere to predetermined production regulations, such as MOQ and MPR, as stipulated by the prescribed guidelines.

- Unavailability of raw materials, which are characterized by extended lead times. This circumstance is compounded by the shared dependency of multiple entities on these resources. As a result, the complexity of the problem escalates, necessitating a comprehensive and detailed approach to efficiently manage these raw materials. Implement meticulous strategies and processes is fundamental to mitigate the repercussions of their unavailability, optimize procurement and production plans, and establish a seamless material flow across the supply chain.
- A diverse range of raw material recipes can be utilized to produce the same material, and various materials may rely on common raw materials, thereby demanding a comprehensive and holistic management approach to address the entirety of the problem.

By conducting a thorough analysis of these factors, a deeper understanding of the intricate nature of the problem is pursued, while simultaneously ensuring the effective implementation of the proposed approach. Furthermore, the identification of these challenges has underscored the imperative need to develop a robust and sophisticated methodology capable of effectively managing the complexity inherent in production environments and meeting the diverse requirements of production planning.

4. TACTICAL PRODUCTION PLANNING OPTIMIZATION APPROACH

The present chapter encompasses the methodology developed to tackle the production planning problem introduced in the previous chapter. Section 4.1. described the main steps to address this challenge. The methodology involves a tactical production planning optimization model, which is presented in Section 4.2. along with its key features and underlying assumptions it relies on. Section 4.3. encompasses the model formulation, elaborating on the model's parameters and decision variables in Section 4.3.1.. The objective function that defines the optimization model is encompassed in Section 4.3.2.. Lastly, Section 4.3.3. focuses on the constraints that are implemented to address the limitations of the company's production planning. At the end of this chapter, Sections 4.4. and 4.5. provide comprehensive explanations of the intended functionalities of the interface and the dashboard, respectively.

4.1. Methodology

Given the opportunities identified, the approach aims at creating a 17-week rolling horizon production plan, in order to aid in planning capacity and production resources, by the development of an optimization tool. The optimization tool is focused on medium-term and short-term tactical planning, excluding long-term planning and daily scheduling. The module was designed to account for the impact on the remaining areas of the logistical operations, ensuring that the results positively impact their performance, and the changes made would not negatively affect other aspects of the production process.

The integration of the model into the company's internal processes has the capability to provide direct benefits to the supply chain department and have an impact on the customer service, purchasing, and production teams. The model is responsible to generate 17-week rolling horizon production plans for the supply chain team by allocating orders to the available filling lines each week and aggregating them into monthly plans for the current and next three months. Moreover, the model can assist the supply chain team in examining the effects of modifications in tactical levers like overtime, cost management, and integrated planning. The optimization module's results provide all the necessary data already required and available for all other teams, including raw materials requirements, the current status of production orders, expected production time, blending necessities, lines capacity, and workforce needs. Therefore, the company will, undoubtedly, benefit from an optimization model that can provide master production plans while adhering to all production constraints and minimizing the global cost function. This enables the company to generate plans more regularly and test various scenarios with varied decision criteria and constraints, which can be developed in a 17-week horizon.

The approach involves creating an optimization model, based on MILP formulation, that generates a weekly production plan for a 17-week period by allocating production orders to each available line. The model formulates decisions by considering cost trade-offs and modifications to the plan's configuration. The primary objective of the model is to minimize operational production costs while adhering to the business and operational constraints that have been set. The model aims to simulate the production process by taking into account various constraints, which are a mathematical representation of the problem's rules, limitations and possibilities. By doing so, the model eliminates unfeasible solutions, ensuring that the optimized plan is acceptable for the planning team and can be implemented.

The proposed approach was broken down into four main steps for the production planning module, as shown in Table 3. It sought to achieve the most cost-effective medium-term production plans for the business. The first step involved analyzing the existing processes to identify the current production planning methodology and all the steps in the production process. This information was used to identify the operational and business constraints that needed to be considered in the optimization model. The second stage was to compile all the data that the optimization model would require as input. The creation of the optimization model was the third and primary phase in this module. The information needed to be organized in a way that the model could use it as input first. Based on the data gathered in step one, the model constraints and objective function were formulated, with the reduction of overall costs as the final result. Finally, several meetings with the company's planning staff were held in order to analyse and validate the developed plans. Additionally, a dashboard was developed that received and altered the model output files. Having a presentation tool that displayed the model results in a thorough and understandable manner would enable the user to comprehend the model's recommendations. By doing this, quick problem identification and effective model refinement were possible.

Table 3: Proposed approach for the production planning optimization model

Process mapping	Map the current planning procedures
	Analyse in detail the production process
	Identify all the operational constraints
Data treatment	Data request
	Data analysis
Optimization model development	Create an input interface with all necessary data
	Implement all the model constraints
	Minimize overall production and inventory costs
	Provide a 17-week production plan and determine the production resources needed to fulfil it
Results visualization	Create a dashboard to analyse and validate the proposed production plans with the company's planning team

Moreover, this approach encompasses the definition of a safe quantity for all binding and forecasted orders that evaluates how much of the future order is safe to say that will materialize in a fixed order. The concept of safe quantity holds great importance, primarily due to the limited reliability of medium-term customer forecasts. This uncertainty poses challenges in effectively aggregating and anticipating orders, requiring the implementation of safe quantity measures. The major benefit of using a safe quantity lies in achieving medium-term plan stability. This approach is conservative, allowing for order anticipation only when there is confidence. In absence of the safe quantity, quantities could not be anticipated without inducing risk in production planning. Thus, this approach reduces the possibility of consolidating orders but demands immediate action and significant plan adjustments as the production date approaches. To further enhance plan stability, there is a benefit that extends to procurement and fleet management. This approach ensures a higher accuracy in the quantities requested for a given week, maximizing raw material service levels, minimizing excessive inventory, and mitigating workforce management issues. Furthermore, there are other benefits, such as reduced setup times, improved overall production flow, and optimized capacity utilization. In conclusion, this approach imparts increased flexibility to the optimization process, fostering enhanced efficiency in decision-making.

The safe quantity is determined based on the historical customer's forecast variability for its due date time horizon. The higher the accuracy of a customer (Equation (1)) for the binding or forecast periods, the higher the portion of the quantities forecasted that is considered safe. The safe quantity is the forecasted quantity for which there is 95% certainty that it will be requested. It is computed, for each SKU per due date time horizon, assuming that the forecast error follows a normal distribution - Figure 20. The shaded region beneath the curve indicates an area equivalent to 5% of the total area. Since the safe quantity corresponds to a 95% level of confidence, it also corresponds to the maximum allowable error of 5% associated with the forecasted quantity, as illustrated by the shaded region.

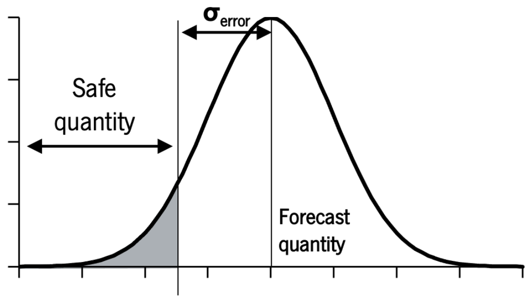

Figure 20: Safe quantity representation in normal distribution of the forecast error

The safe quantity, S, for each forecasted order is estimated by Equation (3).

$$S = 1 - X, \quad \text{with} \quad -1.645 = \frac{X - \mu_X}{\sigma_X} \tag{3}$$

where X is the forecast error, and μ_X, σ_X the mean and standard deviation of X, respectively.

Thus, the methodology related to the safe quantity concept requires a collection of assumptions to ensure its accurate implementation and application:

1. Fixed period depends on the technology (aerosols or liquids) and on the customer.
2. Consider the last received forecast as the most recent for each analyzed week.
3. Fixed forecast quantities considered as the sold quantity for each product and each analyzed week.
4. The error calculated for each gap is the difference between the last forecast and fixed forecast.
5. The safe quantity diminishes the farthest from the fixed period.
6. In SKUs without historical orders, the safe quantity is zero.

Considering the assumptions and relevant data analysis, it can be deduced that the safe quantity varies based on factory, customer, and product, over the planning weeks, reflecting each forecast accuracy. Figure 21 portrays two examples involving distinct customers, showcasing the fluctuation of safe quantities according to the weeks until the production phase. Focusing on the left graph, it is evident that the customer experiences a substantial decline in non-fixed weeks. The safe quantity starts at 100% in initial weeks but dwindles to just 13% by the 12-week mark before production. This phenomenon might arise from the customer's tendency to modify forecasts near fixed deadlines. On the contrary, the graph on the right exemplifies a reliable customer. Despite production occurring with 12 weeks of advance, their ability to maintain elevated forecast accuracy remains evident, substantiated by a safe quantity equivalent to 93%. Through the examination of the two graphs, it is also feasible to highlight that the safe quantity worsens the farthest from the production deadline, as expected.

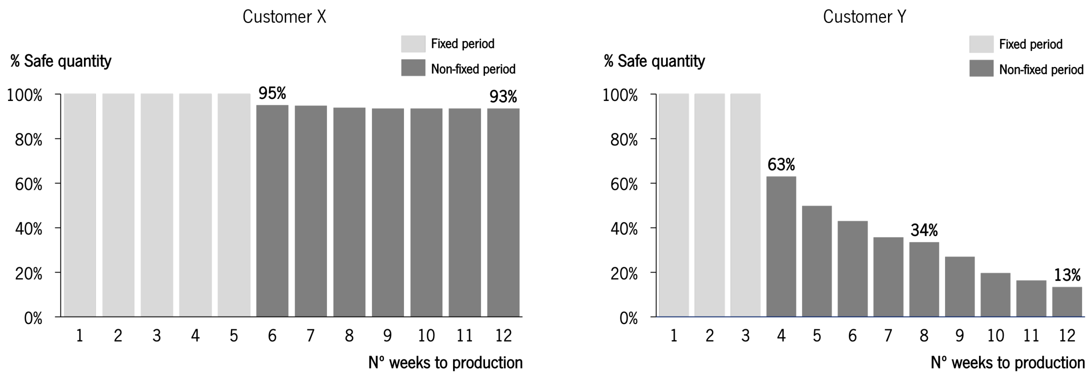

Figure 21: Variability of the safe quantity throughout the number of weeks to production

Another relevant analysis pertains to the distinctive behavior exhibited by the same clients within the scope of the two examined production factories. Upon thorough examination of Figure 22, it becomes possible to distinguish the ratio of safe quantity and, subsequently, the accuracy of the forecast pertaining to each customer within the two factories – the Factory 1 depicted on the left diagram and Factory 2 illustrated on the right diagram. Through a comparative analysis of the values portrayed in the two diagrams, it becomes evident that the methodology will yield differing safe quantity values contingent upon the distinct operational contexts of each factory. To illustrate, in the Factory 1, customer 2 emerges as one of the most reliable clients, boasting a forecast accuracy of roughly 66.8%. In contrast, within the Factory 2, the same customer merely presents an approximate accuracy rate of 45%, consequently categorizing it as one of the less reliable customers. Another pertinent conclusion that can be drawn is that despite manifesting varying safe quantity percentage values, customer 6 emerges as the most erratic client for both manufacturing facilities. In conclusion, it can be observed that, on a broader scale, Factory 2 consistently exhibits higher accuracy in comparison to Factory 1.

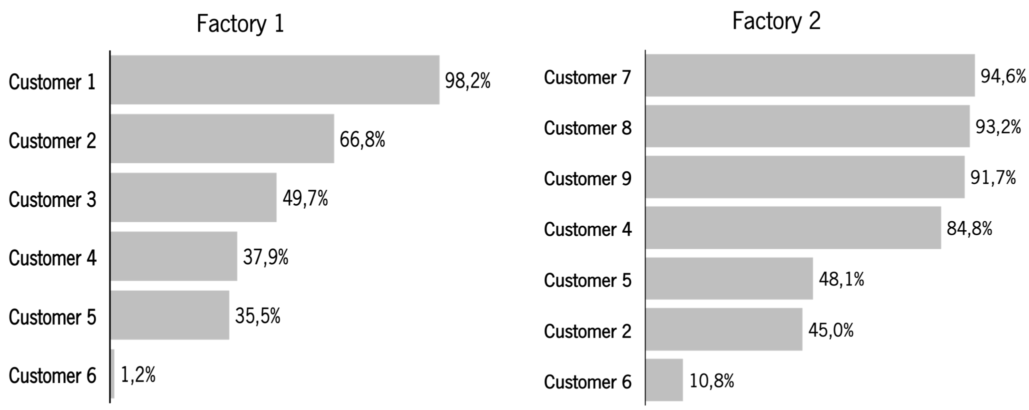

Figure 22: Variability of the safe quantity depending on the customers and factories

Once the value of the safe quantity is calculated, it is allocated to the orders of the binding period to enable the anticipation of a portion or the entirety of those orders. Figure 23 demonstrates the application of the safe quantity concept across three distinct products associated with different customers. This figure serves to elucidate how the proposed methodology addresses the diversity among products from different clients in terms of their fixed, binding, and forecast periods. Furthermore, it highlights varying levels of reliability, as indicated by the proportion of safe quantity in relation to the total forecasted quantity. It is crucial to highlight that the width of the bars represents the total quantity ordered for each period, while the proportion of that quantity deemed safe for anticipation is also indicated.

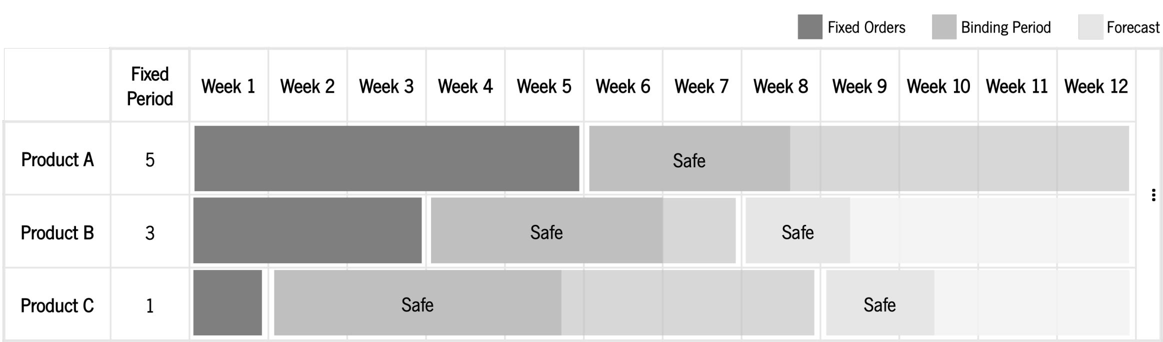

Figure 23: Safe quantity variation across products from different customers over the time horizon

The quantity corresponding to the safe quantity is translated into production batches, which can be anticipated for previous weeks. Non-safe binding or forecast quantities cannot be advanced for production, which means that can only be produced in the same week or subsequent weeks to the delivery week. Consequently, only safe binding or forecast quantities are eligible for production anticipation, while all fixed quantities are eligible for anticipation if other constraints, such as raw materials availability and lines' capacity, are satisfied. Furthermore, the model is designed to prioritize fixed and safe orders over uncertain binding or forecast quantities.

In every run, the model will read a set of inputs related with customer orders, line characteristics, raw materials availability, production routings, setup changes, workforce, and costs.

- **Customer orders:** required forecasted quantities in fixed, binding, and forecast periods. This input is considered the basis for the production plan.
- **Line characteristics:** line configurations per factory, their capacity, productivity, availability, and production constraints.
- **Raw materials availability:** raw materials available stock, or their expected delivery, when required for production.
- **Production routings:** consider product characteristics, namely special production needs (co-packing, valves assemblies, glued trays) and SKU per line compatibility.
- **Setup changes:** setup impact in time and cost, based on changes in bulk and packaging.
- **Workforce:** shift workforce needs per product per line and fixed workforce availability.
- **Costs:** all relevant operational and tactical costs with direct impact in decision making. The involved costs represent the main factor for decision making.

All the inputs mentioned above, along with the parameters set by the planner through the model interface, define the solution space of the model, enabling cost optimization of a 17-week production plan. In addition, this approach provides the planner with a detailed view of the status of each order, with a specific focus on delays, undelivered items, and suggested anticipations by the solution. The main production KPIs can also be obtained, and this information can assist in decision-making regarding capacity planning, workforce requirements, changes in work schedules, or the need for overtime.

The model aims to address numerous business inquiries associated with production order planning. It has been designed to assess each requested order and assign them to a designated production line within a specific planning week. The evaluation and allocation process of an order entails five fundamental decisions and perspectives that are considered, ensuring a methodical approach to achieving efficient production planning.

1. Validate all possible combinations of raw materials and selecting a specific recipe for production based on factors such as raw materials availability, planned deliveries and associated lead times. This recipe specifies the precise quantities and proportions of the raw materials required for production.
2. Identify any components that are currently out of stock for each recipe and taking action to order the necessary raw materials that are missing for production. In this phase, the model examines each recipe and compares it with the current inventory of components.
3. Determine the delay of an order by analyzing the variance between the expected delivery date of the order and the production week in which it is scheduled. This assessment considers the availability of the necessary raw materials for production, as well as the lead time required for these materials to be delivered and ready for use.
4. Evaluate and assess the suitability of each filling line based on criteria such as production speed and cost efficiency to determine the most suitable and cost-effective option. By considering these parameters, the system identifies the filling line that can deliver the quickest production time while maintaining the lowest overall cost.
5. The model analyzes the availability of raw materials and evaluates the capacity of the production lines to determine if it is possible to produce and deliver a portion of the order earlier than originally scheduled - safe quantity.

To successfully implement the optimization model and enhance the efficiency and effectiveness of the proposed approach, a restructure of the planning macro process is required, in order to incorporating the capabilities provided by the module. Therefore, to ensure a successful integration of the optimization module, it was key to redesign the existent planning process represented in Figure 11. The proposed weekly production planning is represented by a process diagram in the Figure 24.

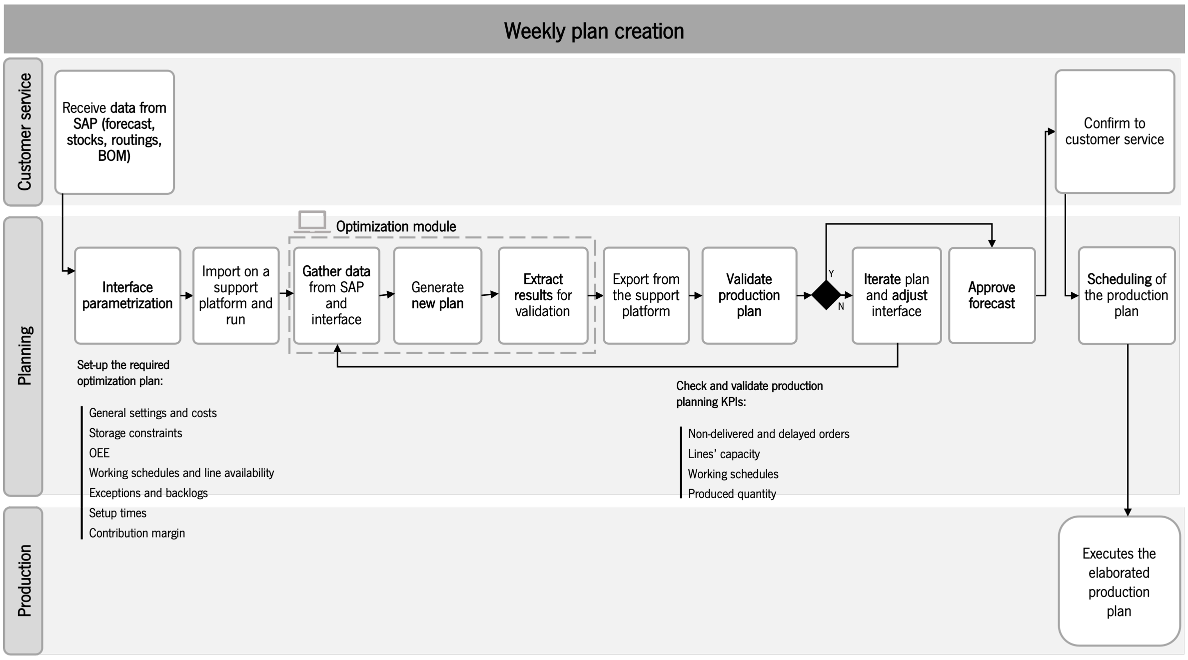

Figure 24: Proposed weekly production planning flowchart

4.1.1. Tactical Levers and Analysis

The planning tool provides valuable assistance to the planning team in developing plans that meet all forecasted orders while minimizing production costs within the company's business environment. It is a critical tool that aids in the decision-making process of the planning team, as it helps them address five critical tactical issues:

1. **Multi-factory planning:** holistic approach to production planning that considers the requirements of both factories and enables sharing of production volumes between the two sites.
2. **Orders aggregation:** aggregation of forecasting orders from stable clients to maximize benefits in aggregated batch productions.
3. **Capacity planning:** assess overtime and undertime possibilities, aligned with order necessities, as well as line usage per shift.
4. **Workforce necessities:** estimate workforce necessities per shift, supporting mid-term shift planning.
5. **Cost and investment analysis:** enables scenario sensitivity analysis according to changes in cost structure, line eligibility and other tactical levers.

4.2. Model's Key Features and Assumptions

To solve the tactical production planning problem, an optimization model based on a linear mixed-integer programming formulation was developed. The model aims to determine and level the production resources required at a detailed level, and, therefore, adopted a weekly time discretization.

Prior to formulating the model, it was necessary to conduct a thorough study of the case, in order to understand all the elements that the company wanted the model's output to include. As shown in the Figure 25, the primary outcome of this tool is the 17-week tactical production plan, where each product quantity is assigned to a specific filing line during a designated week within the defined time horizon. Each generated plan provides the supply chain KPIs associated with it, such as expected line capacity, blending reactors utilization, number of setups, and raw materials availability. The model's output also enables full visibility of all orders planned for each week, sheds light on expected delays, and respective causes and costs, and identifies possible anticipations planned. Furthermore, the tool is able to give detailed information on the number of workers required for each planned week and to issue alerts for changes in the workforce. All plans are accompanied by a comprehensive description and impact of all operational costs associated with it, enabling a cost-productivity analysis. The objective is to create distinct plans for each factory, as these facilities do not engage in shared production activities.

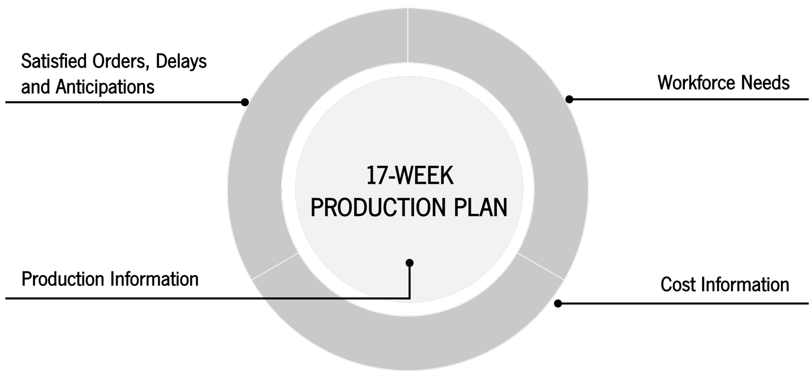

Figure 25: Optimization model's outputs

A rolling horizon technique was implemented to run the optimization model once a week to determine the tactical production planning for the following 17 weeks. In this way, the generated production plan is updated regularly and reflects the company's current conditions.

In the field of optimization, there is often a trade-off between achieving high-quality results and minimizing computational time. Therefore, to obtain results within a reasonable computational time frame, certain assumptions had to be made.

1. Forecasted demand is deterministic and directly extracted from SAP, the ERP system used by the company.
2. Processing times and setup times are deterministic.

3. Setups in the production process are dependent on the sequence of operations and are triggered when there is a transition to a different SKU being manufactured on a production line within a given week. However, as the project did not include scheduling, a setup is considered whenever there is a change in any of the three product characteristics: diameter, height, and product type.
4. The first production in a given week in a certain line has always a setup associated with it.
5. All workers are equally specialized and capable of performing the same jobs with the same efficiency.
6. Backordering is allowed.
7. The model considers a maximum storage capacity of finished goods.
8. The change of working schedule adheres to the country labour laws in which it is implemented.

Nevertheless, these assumptions do not compromise the reliability of the results. In the end, they enabled the model to provide realistic and accurate results in a manageable amount of time. The next section, cover additional assumptions and approximations as necessary.

4.3. Model Formulation

The optimization module employs mixed-integer linear programming in order to create production plans, minimizing overall production costs while respecting operational and business limitations. The developed optimization model is connected to an ERP system and an interface structure that receives all the required inputs. The interface will be elaborated upon in greater detail later, in Section 4.4.

Firstly, the main driver of the production process is the forecasted demand for each period, which is extracted from the company's ERP tool and inputted into the model. Moreover, the ERP plays a crucial role in providing information, such as the comprehensive list of all products along with their relevant characteristics (e.g. MOQ, product type) and constituent components, and compatible combinations of products and production lines as well as significant metrics such as throughput. The ERP system also supplies data on product families and their associated products, real-time stock availability for both products and raw materials, and a detailed list of planned deliveries for each raw material.

Secondly, the input interface structure is utilized to parameterize either global or specific data for each site, encompassing general settings and costs, storage capacity, OEE, global and line-specific working schedules, line availability, exceptions, backlog orders, setup times, and contribution margin.

These parameters and data, sourced from both systems, will be updated prior to each run. The input information described is not exhaustive but has covered the most relevant topics. In the forthcoming sections of this chapter, a comprehensive description of the variables, objective function, and constraints is provided to ensure a thorough representation of all limitations and an accurate depiction of the production process.

4.3.1. Parameters and Decision Variables

In the optimization models' formulation, the definition of parameters and decision variables is important to achieve an optimal solution. Parameters represent the model's behaviour and reflect the characteristics of the planning environment. Decision variables, on the other hand, indicate the decisions that decision-makers can control to achieve optimal production plans. In the context under study, there are several parameters and decision variables that need to be taken into account. The developed optimization model encompasses integer, continuous and binary decision variables. Table 4 provides a comprehensive list of all sets, parameters, and decision variables utilized in the model.

Table 4: Table of notation for the optimization model

Sets	
O	Set of orders to fulfill
K	Set of products
C	Set of product families
R	Set of raw materials
V	Set of BOM recipes
T	Set of periods, $\{1, 2, \ldots, 17\}$
F	Set of factories, $\{Factory\ 1, Factory\ 2\}$
Lf	Set of filling lines
Wh	Set of warehouses, $\{1, 2, 3\}$
D	Set of product diameters
P	Set of product types
A	Set of product heights
H	Set of possible working schedules
Parameters	
dw_o	Delivery week of order o
$dt_{o,k}$	Total forecasted demand of order o for product k
$ds_{o,k}$	Safe quantity of order o for product k
$sti_{o,k}$	Initial stock allocated to order o of product k
MOQ_k	Minimum Order Quantity of product k
MPR_c	Minimum Production Round of product family c
$u_{k,f}$	Units per pallet of product k in factory f
$D_{f,lf,t}$	Number of distinct diameters to be produced in factory f, filling line lf, period t
$P_{f,lf,t}$	Number of distinct product types to be produced in factory f, filling line lf, period t
$A_{f,lf,t}$	Number of distinct heights to be produced in factory f, filling line lf, period t
$sINI_{lf}$	Setup time of INI type (initial) in filling line lf

$sDAP_{lf}$	Setup time of DAP type in filling line lf
sDA_{lf}	Setup time of DA type in filling line lf
sDP_{lf}	Setup time of DP type in filling line lf
sAP_{lf}	Setup time of AP type in filling line lf
sD_{lf}	Setup time of D type (diameter) in filling line lf
sP_{lf}	Setup time of P type (product type) in filling line lf
sA_{lf}	Setup time of A type (height) in filling line lf
sK_{lf}	Setup time of K type (minor setup) in filling line lf
$ahfr_{f,lf,t,h}$	Maximum capacity in regular time of factory f, in filling line lf, period t, using the working schedule h
$ahfn_{f,lf,t,h}$	Maximum capacity in night time of factory f, in filling line lf, period t, using the working schedule h
$ahfe_{f,lf,t,h}$	Maximum capacity in overtime of factory f, in filling line lf, period t, using the working schedule h
$afr_{f,t,h}$	Capacity available during regular hours, when factory f is open, in period t, using the working schedule h
$afn_{f,t,h}$	Capacity available during night hours, when factory f is open, in period t, using the working schedule h
$afe_{f,t,h}$	Capacity available during overtime hours, when factory f is open, in period t, using the working schedule h
$pdtr_{f,lf,t}$	Planned downtime during regular hours, for factory f, filling line lf during period t
$pdtn_{f,lf,t}$	Planned downtime during night hours, for factory f, filling line lf during period t
$pdte_{f,lf,t}$	Planned downtime during overtime hours, for factory f, filling line lf during period t
$aq_{wh,f}$	Capacity available of the warehouse wh of factory f
$wst0_f$	Number of periods t until it is eligible to change the working schedule in the factory f
$wsc_{t,f}$	Binary parameter that equals 1 if it is possible to change the factory's working schedule in period t for factory f, and 0 otherwise
$wsc\_line_{t,f,lf}$	Binary parameter that equals 1 if it is possible to change the filling line's working schedule in period t for factory f, filling line lf, and 0 otherwise
$trab_{f,lf,t}$	Workforce necessities for factory f, filling line lf during period t
$\sigma_{lf,k}$	Throughput of filling line lf to manufacture product k
$ynf_{r,k,v}$	Non-fixed quantity of raw material r required to manufacture product k using recipe v

$yf_{r,k,v}$	Fixed quantity of raw material r required to manufacture product k using recipe v
$\%scrap_r$	Percentage of scrap of raw material r
$stkr0_r$	Initial stock of raw material r
lt_r	Lead time of raw material r
$E0_{r,t}$	Order already placed for raw material r to arrive in period t
M	A number large enough to enforce certain constraints
$WACC$	Weighted Average Cost of Capital
CH_k	Holding cost for product k
$CWP_{k,wh}$	Warehousing cost per product k in warehouse wh
$CPLF_{lf}$	Unitary production cost in filling line lf
$CWHR_f$	Hourly average workforce cost during regular hours in factory f
$CWHN_f$	Hourly average workforce cost during night hours in factory f
$CWHE_f$	Hourly average workforce cost during overtime hours in factory f
CDl_o	Delay cost of order o
CCO_o	Not delivered cost of order o
CFR_f	Hourly opening cost during regular hours of factory f
CFN_f	Hourly opening cost during night hours of factory f
CFE_f	Hourly opening cost during overtime hours of factory f
Decision Variables	
$xk_{o,k,lf,t,v}$	Produced quantity of order o, for product k, filling line lf, during period t, using recipe v
$pp_{k,lf,t}$	Binary variable that equals 1 if product k is produced in filling line lf, in period t, and 0 otherwise
$ppbm_{o,k,lf,t}$	Binary variable that equals 1 if the production bellow MOQ of order o regarding product k was activated in filling line lf, in period t, and 0 otherwise
$pv_{o,k,v,t}$	Binary variable that equals 1 if order o of product k was produced using recipe v in period t, and 0 otherwise
$ff_{c,t}$	Binary variable that equals 1 if product family c was produced in period t, and 0 otherwise
$q_{o,t}$	Binary variable that equals 1 if order o is produced in period t, and 0 otherwise
ns_o	Binary variable that equals 1 if order o is not delivered, and 0 otherwise
Dl_o	Number of weeks of delay of order o
$alf_{f,lf,t}$	Binary variable that equals 1 if, in factory f, filling line lf is open during period t, and 0 otherwise

whe_t	Binary variable that equals 1 if external warehouse is open in period t, and 0 otherwise
$ws_{h,f,t}$	Binary variable that equals 1 if working schedule h is active in factory f during period t, and 0 otherwise
$ws\_line_{h,f,lf,t}$	Binary variable that equals 1 if working schedule h is active in factory f and filling line lf during period t, and 0 otherwise
$hr_{f,lf,t}$	Number of regular shifts used in factory f and filling line lf during the period t
$hn_{f,lf,t}$	Number of night shifts used in factory f and filling line lf during the period t
$he_{f,lf,t}$	Number of overtime shifts used in factory f and filling line lf during the period t
$vn_{f,lf,t}$	Binary variable that equals 1 if is valid to activate night shifts in factory f, filling line lf, in period t, and 0 otherwise
$ve_{f,lf,t}$	Binary variable that equals 1 if is valid to activate overtime shifts in factory f, filling line lf, in period t, and 0 otherwise
$nINI_{f,lf,t}$	Number of INI setups required in factory f, filling line lf, in period t
$nDAP_{f,lf,t}$	Number of DAP setups required in factory f, filling line lf, in period t
$nDA_{f,lf,t}$	Number of DA setups required in factory f, filling line lf, in period t
$nDP_{f,lf,t}$	Number of DP setups required in factory f, filling line lf, in period t
$nAP_{f,lf,t}$	Number of AP setups required in factory f, filling line lf, in period t
$nD_{f,lf,t}$	Number of D setups required in factory f, filling line lf, in period t
$nP_{f,lf,t}$	Number of P setups required in factory f, filling line lf, in period t
$nA_{f,lf,t}$	Number of A setups required in factory f, filling line lf, in period t
$nK_{f,lf,t}$	Number of K setups required in factory f, filling line lf, in period t
$d_{d,f,lf,t}$	Number of distinct diameters d produced in factory f, filling line lf, in period t
$p_{p,f,lf,t}$	Number of distinct product types p produced in factory f, filling line lf, in period t
$a_{a,f,lf,t}$	Number of distinct heights a produced in factory f, filling line lf, in period t
$STK_{o,k,t,wh,v}$	Stock allocated to order o of product k available at the end of period t, stored in warehouse wh, with recipe v
$STKiv_{o,k,v}$	Initial stock allocated to order o of product k, with recipe v
$STR_{r,t}$	Stock of raw material r at the end of period t
$E_{r,t}$	Quantity of raw material r arriving during period t

4.3.2. Objective Function

An optimization model's objective function is indispensable to guiding decision-making and producing the desired results. It serves as a guiding principle by quantifying the goals and objectives of the optimization problem. Since it directly affects the behavior of the optimization model and the outcomes of the optimization process, the formulation of an appropriate objective function is indispensable.

The present problem aims to minimize the objective function, which consists of the sum of all production-related costs for the entire planning horizon. These costs encompass various aspects such as those related to inventory holding, warehousing, filling line usage, workforce, penalties for not delivering or delaying an order, and plant opening expenses.

Inventory Holding Costs

The inventory holding costs are related to the process of carrying inventory during the production. This includes the stock level from the previous period and the produced quantity in each period, under the assumption that inventory is held for half a week. These costs encompass the cost of capital that is obtained by multiplying the unitary holding cost of each product by its stock level and quantity produced, taking into account the Weighted Average Cost of Capital (WACC). Since the latter is annually defined and the considered unit of time is a week, the division by 52 is necessary to convert the annual WACC to a weekly rate.

$$InventoryHoldingCost = \frac{WACC}{52} \sum_{o \in O} \sum_{k \in K} \sum_{t \in T} \sum_{v \in V} CH_k \left(\sum_{wh \in Wh} STK_{o,k,t-1,wh,v} + \sum_{lf \in Lf} \frac{xk_{o,k,lf,t,v}}{2} - \frac{dt_{o,k} \times q_{o,t}}{2} \right) \tag{4}$$

Warehousing Costs

Warehousing costs are the expenses associated with the storage and management of inventory in a warehouse facility. The warehousing costs are calculated by multiplying the unitary warehouse cost of each product by the total stock level of final products within the warehouse facilities.

$$WarehousingCost = \sum_{k \in K} \sum_{wh \in Wh} \left(CWP_{k,wh} \sum_{o \in O} \sum_{t \in T} \sum_{v \in V} STK_{o,k,t,wh,v} \right) \tag{5}$$

Filling Line Usage Costs

Filling line costs refer to the expenses associated with using production lines in a manufacturing facility. These expenses are related to the operational use of particular filling lines in the production process. The aforementioned costs are estimated by considering filling line utilization, equipment maintenance and depreciation, as well as energy consumption. In this way, filling line usage costs are determined by multiplying the unitary production cost in each filling line by the time spent producing the required quantities, as shown in the equation presented below.

$$FillingLineUsageCost = \sum_{lf \in Lf} \left(CPLF_{lf} \sum_{k \in K} \frac{1}{\sigma_{lf,k}} \sum_{o \in O} \sum_{t \in T} \sum_{v \in V} xk_{o,k,lf,t,v} \right) \tag{6}$$

Workforce Costs

Workforce costs in the production field cover the expenses related to the labour force involved in the production process. These costs include various components associated with hiring and managing the crew responsible for performing production operations and contributing to overall production activities. The workforce costs depend on the unitary labour cost for regular (during day time), night and overtime hours. Therefore, the costs are obtained by multiplying the unitary cost by the corresponding time allocated to the production process, according to the line working schedule selected, in accordance with the equation below.

$$\begin{aligned} WorkforceCost = \sum_{h \in H} \sum_{f \in F} \sum_{lf \in Lf} \sum_{t \in T} ws\_line_{h,f,lf,t} \times trab_{f,lf,t} \\ \left(ahfr_{f,lf,t,h} \times CWHR_f + ahfn_{f,lf,t,h} \times CWHN_f + ahfe_{f,lf,t,h} \times CWHE_f \right) \end{aligned} \tag{7}$$

Delay Costs

Delay costs, as the name suggests, include the penalties associated with shipping an order in a week later than the agreed delivery week. These expenses represent the gradual loss of value of the product resulting from the delay in fulfilling the demanded order. To clarify, the costs incurred due to the delay reflect the incremental depreciation in the product's value over time.

$$DelayCost = \sum_{o \in O} CDl_o \times Dl_o \sum_{k \in K} \sum_{lf \in Lf} \sum_{\substack{t \in T \\ t > dw_o}} \sum_{v \in V} xk_{o,k,lf,t,v} \tag{8}$$

Not Deliver Costs

Not deliver costs correspond to the penalties incurred when an ordered product is not delivered to the customer. These costs are calculated by estimating the opportunity cost incurred by losing a potential sale of the product. In other words, they represent the potential revenue that would have been generated if the product had been successfully delivered to the customer. It is important to notice that the model was developed to increase the penalty on the cancellation of orders with delivery weeks that are closer to the plan generation date. Taking this into consideration, the not deliver costs are determined by:

$$NotDeliverCost = \sum_{o \in O} \sum_{k \in K} CCO_o \times ns_o \times dt_{o,k}(17 - dw_o + 1) \tag{9}$$

Factory Opening Costs

Factory opening costs refer to the expenses associated with preparing and operating a plant for production runs. These costs are calculated by summing the expenses of opening each factory during regular, night and overtime hours, taking into consideration the corresponding time available in the selected working schedule.

$$\begin{aligned} FactoryOpeningCost = \sum_{h \in H} \sum_{f \in F} \sum_{t \in T} ws_{h,f,t}(CFR_f \times afr_{f,t,h} + \\ CFN_f \times afn_{f,t,h} + CFE_f \times afe_{f,t,h}) \end{aligned} \tag{10}$$

Concluding this section, and considering all the terms above described, the problem consists in minimizing the objective function, that is:

$$\begin{aligned} \text{Minimize}\Big(InventoryHoldingCost + WarehousingCost \\ + FillingLineUsageCost + WorkforceCost \\ + DelayCost + NotDeliverCost + FactoryOpeningCost\Big) \end{aligned} \tag{11}$$

4.3.3. Constraints

Once the objective function has been determined, we can move on to the formulation of the problem's constraints, that are responsible to define the possible solution space. In the context of production planning, constraints represent the real-world limitations and requirements that must be considered to ensure practical and feasible solutions. All the pertinent constraints that are part of the model are discussed in this section. The constraints have been organized into sets that focus on common areas to make it easier to understand.

Filling Lines

As depicted in Figures 9 and 10, the manufacturing process of the products sold by the company involves three distinct macro stages: blending, auxiliary operations, and filling. However, it is important to note that the scope of the current project is limited to the production process specifically carried out in the filling lines, excluding the blending and auxiliary lines.

One of the most important constraints for the operation of the model is the one that enforces that the production of a given product in a given filling line requires the activation of the specified filling line, determined by the variable $alf_{f,lf,t}$. This is achieved through the constraint provided hereafter, which links the total quantity of a given product of a certain order produced in each period in a given filling line, consuming a specific recipe, with the binary variable $alf_{f,lf,t}$.

$$\sum_{o \in O} \sum_{k \in K} \sum_{v \in V} xk_{o,k,lf,t,v} \leq M \times \sum_{f \in F} alf_{f,lf,t}, \quad lf \in Lf, t \in T \tag{12}$$

Orders Management

Each production order can have two mutually exclusive statuses: delivered or cancelled. These statuses are determined by the values of the binary variables ns_o and $q_{o,t}$. An order is considered delivered if the required demand is met, either by consuming the initial stock or by producing the product. However, if an order is fully produced in a week prior to the scheduled delivery week, it is assumed that the order will be delivered only in the agreed delivery week. Therefore, the upcoming three constraints were implemented to manage the status of each production order.

$$ns_o + \sum_{t \in T} q_{o,t} = 1, \quad o \in O \tag{13}$$

$$\sum_{k \in K} \Big(dt_{o,k} - sti_{o,k} - \sum_{lf \in Lf} \sum_{t \in T} \sum_{v \in V} xk_{o,k,lf,t,v}\big) \leq M\Big(1 - \sum_{\substack{t \in T \\ t \geq dw_o}} q_{o,t}\Big), \quad o \in O \tag{14}$$

$$q_{o,t} = 0, \quad o \in O, \;\; t < dw_o \tag{15}$$

Additionally, if an order assumes the status of being produced ($q_{o,t} = 1$), it is possible to meet the customer's demand on time or delay the order and deliver it in a later week. Thus, the delay time is a crucial KPI to be determined. The delay value, in weeks, can be calculated by implementing and applying the constraint bellow.

$$Dl_o = \sum_{\substack{t \in T \\ t \geq dw_o}} q_{o,t}(t - dw_o), \quad o \in O \tag{16}$$

Orders Production

The following set of constraints focuses on managing and ensuring the accurate production of ordered products. These constraints establish limits for the production quantity when an order is to be delivered to the customer, as well as the stock levels throughout the planning horizon.

Firstly, to prevent overproduction and minimize waste, a constraint was formulated to restrict the quantity produced. This constraint ensures that the production quantity does not exceed the quantity ordered by the customer, as long as the factory meets all the necessary conditions for delivering the order. Conversely, if it is not possible to fulfil the entire customer demand and the order is cancelled, the production of the respective product must be set to zero.

$$\sum_{lf \in Lf} \sum_{t \in T} \sum_{v \in V} xk_{o,k,lf,t,v} + sti_{o,k}(1 - ns_o) = dt_{o,k}(1 - ns_o), \quad o \in O, k \in K \tag{17}$$

Secondly, and since the optimization module encompasses the definition of a safe quantity in order to anticipate some production, was mandatory to limit the expected production anticipated. In this way, the production can be prepared for potential and future demand. This means that the production should be adjusted to match the predetermined safe quantity if a customer's product allows for it. The safe quantity must be produced or deducted to the stock level until the maximum value of the variable $ds_{o,k}$ is reached. This mathematical relation is represented in constraint (18) given below. Therefore, if there is sufficient initial stock available, the production of that particular product should be set to the null value, constrained by the Equation (19).

$$\sum_{v \in V} \left(STKiv_{o,k,v} + \sum_{lf \in Lf} \sum_{\substack{t \in T \\ t < dw_o}} xk_{o,k,lf,t,v} \right) \leq ds_{o,k}, \quad o \in O, k \in K, \;\; ds_{o,k} \geq sti_{o,k} \tag{18}$$

$$\sum_{k \in K} \sum_{lf \in Lf} \sum_{\substack{t \in T \\ t < dw_o}} \sum_{v \in V} xk_{o,k,lf,t,v} = 0, \quad o \in O, \;\; ds_{o,k} < sti_{o,k} \tag{19}$$

As a result to each production or delivery being completed, the stock level of a product needs to be adjusted and updated. Hence, the stock level can be determined by the application of the constraint (20) indicated below. This mathematical equation indicates that the stock level existent in the end of a given week is determined by adding the stock from the previous week with the quantity produced and subtracting the quantity of that product delivered in the current week.

However, it is important to highlight a minor distinction when it comes to determining the stock in the first week of the planning horizon. In this situation, the variable representing the stock from the previous week ($STK_{o,k,t-1,wh,v}$) should be replaced by the variable representing the initial stock of the same product, using a specific recipe ($STKiv_{o,k,v}$). This specific scenario is ensured through the implementation of the restriction (21).

$$\begin{aligned} \sum_{wh \in Wh} \sum_{v \in V} STK_{o,k,t-1,wh,v} + \sum_{lf \in Lf} \sum_{v \in V} xk_{o,k,lf,t,v} \\ -dt_{o,k} \times q_{o,t} = \sum_{wh \in Wh} \sum_{v \in V} STK_{o,k,t,wh,v}, \quad o \in O, k \in K, \;\; t > 1 \end{aligned} \tag{20}$$

$$\begin{aligned} &\sum_{v \in V} STKiv_{o,k,v} + \sum_{lf \in Lf} \sum_{v \in V} xk_{o,k,lf,t,v} - dt_{o,k} \times q_{o,t} \\ &= \sum_{wh \in Wh} \sum_{v \in V} STK_{o,k,t,wh,v}, \quad o \in O, k \in K, \;\; t = 1 \end{aligned} \tag{21}$$

Product Management

The product management constraints aims to enforce the company's rules regarding the production of specific items. In this field, there are two rules: production must comply with the MOQ of each product, unless the production of product in a specific week is considered an exception by the planning team; production of products belonging to product families must adhere to the MPR of the family.

In this way, this set of constraints can be categorized into three pairs, each one consisting of similar formulations but applicable to different products. The first pair includes constraints that enforce the MOQ requirement for production. The second pair comprises constraints for products that do not need to be produced in quantities exceeding the MOQ and, therefore, are considered as exceptions. Lastly, the third pair restricts the production of items belonging to the same product family, ensuring compliance with the family's MPR.

Expanding on the first set of constraints, constraint (22) guarantees that the production quantity of each non-family product, excluding any exceptions, adheres to the designated and individual MOQ. Complementing the first restriction, constraint (23) is responsible for activating the production of a specific product, indicated by the variable $pp_{k,lf,t}$.

$$\sum_{o \in O} \sum_{v \in V} xk_{o,k,lf,t,v} \geq MOQ_k \times pp_{k,lf,t}, \quad k \in K, lf \in Lf, t \in T \tag{22}$$

$$\sum_{o \in O} \sum_{v \in V} xk_{o,k,lf,t,v} \leq M \times pp_{k,lf,t}, \quad k \in K, lf \in Lf, t \in T \tag{23}$$

To clarify, the model receives as input exceptions concern three different classes. One of the classes includes products to be delivered in a specific delivery week that, during production, do not require to comply with the established MOQ (due to component or product clearance, internal agreements with the client, among others). In these cases, and following the same rationale as explained earlier, the exceptional products need to comply with the mathematical expressions provided below.

$$\sum_{v \in V} xk_{o,k,lf,t,v} \geq dt_{o,k} \times ppbm_{o,k,lf,t}, \quad o \in O, k \in K, lf \in Lf, t \in T \tag{24}$$

$$\sum_{v \in V} xk_{o,k,lf,t,v} \leq M \times ppbm_{o,k,lf,t}, \quad o \in O, k \in K, lf \in Lf, t \in T \tag{25}$$

To enforce compliance with the second rule, which states that the production of products within a product family must adhere to the MPR requirement of that family, certain constraints are applied to products belonging to the same family. The upcoming pair of constraints define the limitations for these products, allowing them to be combined and produced together in a batch within the same filling line and planning week. This ensures that the total quantity produced aligns with the established quantity set by the corresponding MPR.

$$\sum_{\substack{k \in K \\ \text{family}(k)=c}} \sum_{lf \in Lf} \sum_{o \in O} \sum_{v \in V} xk_{o,k,lf,t,v} \geq MPR_c \times ff_{c,t}, \quad c \in C, t \in T \tag{26}$$

$$\sum_{\substack{k \in K \\ \text{family}(k)=c}} \sum_{lf \in Lf} \sum_{o \in O} \sum_{v \in V} xk_{o,k,lf,t,v} \leq M \times ff_{c,t}, \quad c \in C, t \in T \tag{27}$$

Setups Definition

In the given context, a setup is performed whenever there is a transition between two consecutive products on a specific production line. It is important to note that the setups applied are not sequence-dependent, since the scope of the project does not comply with scheduling. In this way, the setups considered involve, only, changes in their macro characteristics – diameter (D), height (A), and product type (P). Moreover, the beginning of production on a filling line, each week, requires an initial setup with longer duration (INI) to prepare and ensure the line is ready for operation. Additionally, switching between products with the same characteristics involves a setup of shorter duration, referred to as K.

To ensure the proper execution of each setup type, it is necessary to limit the number of setups conducted to the number of different product characteristics manufactured on a specific filling line each week. Therefore, for example, the sum of the setups involving a change in product diameter ($nINI_{f,lf,t}$, $nDAP_{f,lf,t}$, $nDA_{f,lf,t}$, $nDP_{f,lf,t}$, and $nD_{f,lf,t}$) must be equal to the number of different diameters produced in each filling line during each planning week. The same principle applies to the other two macro characteristics of the products, namely height and product type.

$$\begin{aligned} nINI_{f,lf,t} + nDAP_{f,lf,t} + nDA_{f,lf,t} + nDP_{f,lf,t} + \\ nD_{f,lf,t} = \sum_{d \in D} d_{d,f,lf,t}, \quad f \in F, lf \in Lf, t \in T \end{aligned} \tag{28}$$

$$\begin{aligned} nINI_{f,lf,t} + nDAP_{f,lf,t} + nDA_{f,lf,t} + nAP_{f,lf,t} + \\ nA_{f,lf,t} = \sum_{a \in A} a_{a,f,lf,t}, \quad f \in F, lf \in Lf, t \in T \end{aligned} \tag{29}$$

$$\begin{aligned} nINI_{f,lf,t} + nDAP_{f,lf,t} + nAP_{f,lf,t} + nDP_{f,lf,t} + \\ nP_{f,lf,t} = \sum_{p \in P} p_{p,f,lf,t}, \quad f \in F, lf \in Lf, t \in T \end{aligned} \tag{30}$$

Furthermore, it was important to limit the overall number of setups performed on a filling line to match the total number of products manufactured on that line, during each week. Thus, the sum of the total number of setups should be equal to the sum of the binary variables ($pp_{k,lf,t}$ and $ppbm_{o,k,lf,t}$) indicating the activation of each product on the filling line, within the given time frame.

$$nINI_{f,lf,t} + nDAP_{f,lf,t} + nDA_{f,lf,t} + nAP_{f,lf,t} + nDP_{f,lf,t} + nD_{f,lf,t} + nA_{f,lf,t}$$
$$+nP_{f,lf,t} + nK_{f,lf,t} = \sum_{k\in K}\left(pp_{k,lf,t} + \sum_{o\in O} ppbm_{o,k,lf,t}\right), \quad f \in F, lf \in Lf, t \in T \tag{31}$$

The intrinsic nature of the initial setup (INI) is that it is performed at the beginning of each production run on a specific filling line. Therefore, an INI setup can assume a maximum value of 1 and is performed (i.e., equals 1) when the filling line is active for production.

$$nINI_{f,lf,t} = alf_{f,lf,t}, \quad f \in F, lf \in Lf, t \in T \tag{32}$$

The subsequent group of constraints is employed to restrict the solution space for each setup performed based on the number of diameters, heights, and product types present in the routines ($D_{f,lf,t}$, $A_{f,lf,t}$ and $P_{f,lf,t}$). Consequently, the activation of each setup type is closely linked to the binary variable that determines whether a specific filling line is active during a given planning week.

$$nDAP_{f,lf,t} \leq alf_{f,lf,t}\left(D_{f,lf,t} - 1\right)\left(A_{f,lf,t} - 1\right)\left(P_{f,lf,t} - 1\right), \quad f \in F, lf \in Lf, t \in T \tag{33}$$

$$nDA_{f,lf,t} \leq alf_{f,lf,t}\left(D_{f,lf,t} - 1\right)\left(A_{f,lf,t} - 1\right), \quad f \in F, lf \in Lf, t \in T \tag{34}$$

$$nDP_{f,lf,t} \leq alf_{f,lf,t}\left(D_{f,lf,t} - 1\right)\left(P_{f,lf,t} - 1\right), \quad f \in F, lf \in Lf, t \in T \tag{35}$$

$$nAP_{f,lf,t} \leq alf_{f,lf,t}\left(A_{f,lf,t} - 1\right)\left(P_{f,lf,t} - 1\right), \quad f \in F, lf \in Lf, t \in T \tag{36}$$

$$nD_{f,lf,t} \leq alf_{f,lf,t}\left(D_{f,lf,t} - 1\right), \quad f \in F, lf \in Lf, t \in T \tag{37}$$

$$nA_{f,lf,t} \leq alf_{f,lf,t}\left(A_{f,lf,t} - 1\right), \quad f \in F, lf \in Lf, t \in T \tag{38}$$

$$nP_{f,lf,t} \leq alf_{f,lf,t}\left(P_{f,lf,t} - 1\right), \quad f \in F, lf \in Lf, t \in T \tag{39}$$

To activate the binary variables related to each product's characteristics used in constraints (28), (29) and (30), two complementary expressions were formulated for each characteristic. The first one enforces that the production of a product from a given order, represented by the variable $xk_{o,k,lf,t,v}$, requires the activation of all three characteristics. The second constraint ensures that in cases of zero production, the binary variables associated with the characteristics should remain inactive.

$$\sum_{\substack{k \in K \\ \text{diameter}(k)=d}} \sum_{o \in O} \sum_{v \in V} xk_{o,k,lf,t,v} \leq M \times d_{d,f,lf,t}, \quad d \in D, f \in F, lf \in Lf, t \in T \tag{40}$$

$$\sum_{\substack{k \in K \\ \text{diameter}(k)=d}} \sum_{o \in O} \sum_{v \in V} xk_{o,k,lf,t,v} \geq d_{d,f,lf,t}, \quad d \in D, f \in F, lf \in Lf, t \in T \tag{41}$$

$$\sum_{\substack{k \in K \\ \text{height}(k)=a}} \sum_{o \in O} \sum_{v \in V} xk_{o,k,lf,t,v} \leq M \times a_{a,f,lf,t}, \quad a \in A, f \in F, lf \in Lf, t \in T \tag{42}$$

$$\sum_{\substack{k \in K \\ \text{height}(k)=a}} \sum_{o \in O} \sum_{v \in V} xk_{o,k,lf,t,v} \geq a_{a,f,lf,t}, \quad a \in A, f \in F, lf \in Lf, t \in T \tag{43}$$

$$\sum_{\substack{k \in K \\ \text{product type}(k)=p}} \sum_{o \in O} \sum_{v \in V} xk_{o,k,lf,t,v} \leq M \times p_{p,f,lf,t}, \quad p \in P, f \in F, lf \in Lf, t \in T \tag{44}$$

$$\sum_{\substack{k \in K \\ \text{product type}(k)=p}} \sum_{o \in O} \sum_{v \in V} xk_{o,k,lf,t,v} \geq p_{p,f,lf,t}, \quad p \in P, f \in F, lf \in Lf, t \in T \tag{45}$$

Workforce Management

The workforce management restrictions are responsible to ensure that the process of choosing both factory and filling lines working schedules respect two main premises. Firstly, it's only possible to have one active working schedule for the whole factory and for each filling line. Secondly, the factory's working schedule must remain the same for a number of consecutive weeks, stated by the variable $wst0$. This means that once a schedule is chosen, it should be maintained without changes for $wst0$ weeks. To satisfy the second premise, a constraint should be applied to ensure that when it's not possible to change the working schedule, it should remain the same as the previously chosen schedule.

The first premise is achieved through the constraint (46), which establishes that the sum of all binary variables related to the active working schedule for each planning week ($ws_{h,f,t}$), must equal 1.

$$\sum_{h \in H} ws_{h,f,t} = 1, \quad f \in F, t \in T \tag{46}$$

The second premise is achieved through the binary parameter $wsc_{t,f}$, which takes the value of 1 if it is possible to change the working schedule in period t for factory f, and 0 otherwise. Therefore, when $wsc_{t,f}$ equals 1, the module has the flexibility to choose any working schedule within the range of possibilities. On the other hand, when $wsc_{t,f}$ is 0, the active working schedule for factory f in period t must be the same as the active working schedule for the same factory in the period $t-1$. It is important to underscore that the operational schedules of the factories for the initial weeks are established and parameterized by the planning team. As a result, the model is required to adhere to this requirement and is precluded from altering the working schedules during the designated parameterized weeks.

$$ws_{h,f,t}(1 - wsc_{t,f}) = ws_{h,f,t-1}(1 - wsc_{t,f}), \quad h \in H, f \in F, \ \ t \geq wst0_f + 1 \tag{47}$$

The process of selecting the most suitable working schedule for each filling line is based on the same rationale mentioned for the factory's working schedule. However, the variables used in these equations specifically pertain to the filling lines. It is important to note that, similar to the factory working schedule, the operational schedule for each filling line during the initial four weeks is defined by the planning team as a parameter. In this way, the model is strictly prohibited from making changes to these predefined schedules. Additionally, in order to manage the process of hiring work teams, it is possible to change the line schedule, but it must remain unchanged for four consecutive weeks.

$$\sum_{h \in H} ws\_line_{h,f,lf,t} = 1, \quad f \in F, lf \in Lf, t \in T \tag{48}$$

$$\begin{aligned} ws\_line_{h,f,lf,t}(1 - wsc\_line_{t,f,lf}) = ws\_line_{h,f,lf,t-1}(1 - wsc\_line_{t,f,lf}), \\ h \in H, f \in F, lf \in Lf, \ \ t \geq 5 \end{aligned} \tag{49}$$

Lastly, in order to ensure the appropriate selection of the active working schedules, it is necessary to limit the working schedule for each filling line in a way that it does not exceed the total available hours set for the factory, as demonstrated in the equation below.

$$\begin{aligned} &\sum_{h \in H} ws\_line_{h,f,lf,t}\Big(ahfr_{f,lf,t,h} + ahfn_{f,lf,t,h} + ahfe_{f,lf,t,h}\Big) \\ \leq &\sum_{h \in H} ws_{h,f,t}\Big(afr_{f,t,h} + afn_{f,t,h} + afe_{f,t,h}\Big), \quad f \in F, lf \in Lf, t \in T \end{aligned} \tag{50}$$

Line Capacity

Line capacity constraints aim to ensure production planning while respecting the capacity limits of both filling lines and the overall factory. Thus, it is crucial to ensure that the time spent on production and setup does not surpass the total available time. The availability, determined by total time or shifts, is set by choosing a working schedule, considering planned downtimes for each filling line.

$$\begin{aligned}\sum_{o\in O}\sum_{k\in K}\sum_{v\in V}\frac{xk_{o,k,lf,t,v}}{\sigma_{lf,k}} + nINI_{f,lf,t}\times sINI_{lf} + nDAP_{f,lf,t}\times sDAP_{lf}\\ +nDA_{f,lf,t}\times sDA_{lf} + nDP_{f,lf,t}\times sDP_{lf} + nAP_{f,lf,t}\times sAP_{lf} + nD_{f,lf,t}\times sD_{lf}\\ +nA_{f,lf,t}\times sA_{lf} + nP_{f,lf,t}\times sP_{lf} + nK_{f,lf,t}\times sK_{lf}\\ \leq \sum_{h\in H} ws\_line_{h,f,lf,t}(ahfr_{f,lf,t,h} + ahfn_{f,lf,t,h} + ahfe_{f,lf,t,h})\\ -(pdtr_{f,lf,t} + pdtn_{f,lf,t} + pdte_{f,lf,t}),\quad f\in F, lf\in Lf, t\in T\end{aligned} \tag{51}$$

$$\begin{aligned}8(hr_{f,lf,t} + hn_{f,lf,t}) + he_{f,lf,t} \geq \sum_{o\in O}\sum_{k\in K}\sum_{v\in V}\frac{xk_{o,k,lf,t,v}}{\sigma_{lf,k}}\\ +nINI_{f,lf,t}\times sINI_{lf} + nDAP_{f,lf,t}\times sDAP_{lf} + nDA_{f,lf,t}\times sDA_{lf}\\ +nDP_{f,lf,t}\times sDP_{lf} + nAP_{f,lf,t}\times sAP_{lf} + nD_{f,lf,t}\times sD_{lf}\\ +nA_{f,lf,t}\times sA_{lf} + nP_{f,lf,t}\times sP_{lf} + nK_{f,lf,t}\times sK_{lf},\quad f\in F, lf\in Lf, t\in T\end{aligned} \tag{52}$$

The following three constraints determine the number of regular and nigh shifts, and overtime hours, respectively, required to adhere to the production plan. Their purpose is to ensure that staffing requirements do not surpass the total available time of the selected working schedule for each line.

$$8hr_{f,lf,t} + pdtr_{f,lf,t} \leq \sum_{h\in H} ahfr_{f,lf,t,h}\times ws\_line_{h,f,lf,t},\quad f\in F, lf\in Lf, t\in T \tag{53}$$

$$8hn_{f,lf,t} + pdtn_{f,lf,t} \leq \sum_{h\in H} ahfn_{f,lf,t,h}\times ws\_line_{h,f,lf,t},\quad f\in F, lf\in Lf, t\in T \tag{54}$$

$$he_{f,lf,t} + pdte_{f,lf,t} \leq \sum_{h \in H} ahfe_{f,lf,t,h} \times ws\_line_{h,f,lf,t}, \quad f \in F, lf \in Lf, t \in T \tag{55}$$

The upcoming group of constraints ensures the proper activation of night shifts. This activation is subject to two conditions ((56) and (57)): night shifts should be activated when the capacity of regular shifts is insufficient, and the activation of night capacity requires that the regular capacity reaches its maximum limit. Specifically, constraint (58) mandates the activation of night shifts and, consequently, the binary variable $vn_{f,lf,t}$, by comparing it with the variable $hn_{f,lf,t}$.

$$\begin{aligned} &\sum_{h \in H} ahfr_{f,lf,t,h} \times ws\_line_{h,f,lf,t} - pdtr_{f,lf,t} - \sum_{o \in O} \sum_{k \in K} \sum_{v \in V} \frac{xk_{o,k,lf,t,v}}{\sigma_{lf,k}} \\ &-(nINI_{f,lf,t} \times sINI_{lf} + nDAP_{f,lf,t} \times sDAP_{lf} + nDA_{f,lf,t} \times sDA_{lf} \\ &+nDP_{f,lf,t} \times sDP_{lf} + nAP_{f,lf,t} \times sAP_{lf} + nD_{f,lf,t} \times sD_{lf} \\ &+nA_{f,lf,t} \times sA_{lf} + nP_{f,lf,t} \times sP_{lf} + nK_{f,lf,t} \times sK_{lf}) \\ &\leq M(1 - vn_{f,lf,t}), \quad f \in F, lf \in Lf, t \in T \end{aligned} \tag{56}$$

$$\begin{aligned} &\sum_{h \in H} ahfr_{f,lf,t,h} \times ws\_line_{h,f,lf,t} - 8hr_{f,lf,t} - pdtr_{f,lf,t} \leq M(1 - vn_{f,lf,t}), \\ &f \in F, lf \in Lf, t \in T \end{aligned} \tag{57}$$

$$hn_{f,lf,t} \leq M \times vn_{f,lf,t}, \quad f \in F, lf \in Lf, t \in T \tag{58}$$

A similar rationale is applied when it comes to activating the overtime or extra schedule. In this case, the activation of extra hours requires that the available time in regular and night shifts, considering the regimes' planned downtimes, is insufficient and fully utilized to production. Constraints (59), (60) given below are applicable for each filling line of a specific factory during each week of the planning horizon, and constraint (61) that follows ensures compliance with the mentioned conditions and enforce the activation of the necessary variables, related with the utilization of extra hours, for the proper functioning of the optimization model.

Furthermore, in relation to the activation of extra hours, an additional constraint, namely Equation (62), needs to be included. This constraint illustrates and reinforces the condition that the extra hours can only be utilized if the night shifts are active during a given week in a specific filling line.

$$\sum_{h\in H} ws\_line_{h,f,lf,t}(ahfr_{f,lf,t,h} + ahfn_{f,lf,t,h}) - pdtr_{f,lf,t} - pdtn_{f,lf,t}$$
$$- \sum_{o\in O}\sum_{k\in K}\sum_{v\in V}\frac{xk_{o,k,lf,t,v}}{\sigma_{lf,k}} - (nINI_{f,lf,t} \times sINI_{lf}$$
$$+nDAP_{f,lf,t} \times sDAP_{lf} + nDA_{f,lf,t} \times sDA_{lf} + nDP_{f,lf,t} \times sDP_{lf} \tag{59}$$
$$+nAP_{f,lf,t} \times sAP_{lf} + nD_{f,lf,t} \times sD_{lf} + nA_{f,lf,t} \times sA_{lf}$$
$$+nP_{f,lf,t} \times sP_{lf} + nK_{f,lf,t} \times sK_{lf}) \leq M(1 - ve_{f,lf,t}),$$
$$f \in F, lf \in Lf, t \in T$$

$$he_{f,lf,t} \leq M \times ve_{f,lf,t}, \quad f \in F, lf \in Lf, t \in T \tag{60}$$

$$\sum_{h\in H} ahfn_{f,lf,t,h} \times ws\_line_{h,f,lf,t} - 8hn_{f,lf,t} - pdtn_{f,lf,t} \leq M(1 - ve_{f,lf,t}),$$
$$f \in F, lf \in Lf, t \in T \tag{61}$$

$$ve_{f,lf,t} \leq vn_{f,lf,t}, \quad f \in F, lf \in Lf, t \in T \tag{62}$$

Warehouse Capacity

The constraints related to warehouse capacity aim to ensure the proper management of inventory stored in the warehouses of both factories and, consequently, prevent overproduction of finished products. The limitations regarding warehouse capacity can be represented by two mathematical equations.

The first equation ensures that the existing stock of finished goods does not surpass the maximum pallet capacity that each warehouse can handle.

$$\sum_{o\in O}\sum_{k\in K}\sum_{v\in V}\frac{STK_{o,k,t,wh,v}}{u_{k,f}} \leq aq_{wh,f} \times whe_t, \quad t \in T, wh \in Wh, f \in F \tag{63}$$

The second equation applies specifically to Factory 1, which has two warehouses — an internal and an external one. This constraint states that the specified stock of finished products can only be stored in the external warehouse when the internal warehouse ($wh = 1$) is at full capacity.

$$aq_{wh=1,f} - \sum_{o \in O} \sum_{k \in K} \sum_{wh \in \{1,2\}} \sum_{v \in V} \frac{STK_{o,k,t,wh,v}}{u_{k,f}} < M\left(1 - whe_t\right), \quad t \in T, \quad f = Factory\ 1 \tag{64}$$

Raw Materials

Raw materials play a vital role in the manufacturing process as they serve as the fundamental building blocks for creating various products. Therefore, ensuring the efficient management of raw material needs and deliveries is an essential component of the designed optimization model.

The first constraint related to raw materials management ensures that the production of a specific finished good only occurs if the constituent raw materials for the product are available at the time of production (which means that must be accessible in the week before the production begins), taking into account the expected percentage of scrap. These constraints also consider the distinction between the fixed quantity of each component ($yf_{r,k,v}$) and the non-fixed quantity ($ynf_{r,k,v}$), required for a specific product.

$$(1 + \%scrap_r) \sum_{o \in O} \sum_{k \in K} \sum_{v \in V} \left(\sum_{lf \in Lf} \frac{ynf_{r,k,v}}{1000} \times xk_{o,k,lf,t,v} + pv_{o,k,v,t} \times yf_{r,k,v} \right) \leq STR_{r,t-1}, \quad r \in R, t \in T \text{ with } t \neq 1 \tag{65}$$

Additionally, it was necessary to create a specific constraint to determine the stock of each raw material after every production, ensuring an updated and realistic value. As stated by the subsequent constraint, the stock of each raw material at the end of a given planning week can be calculated by subtracting the raw material consumption from the existing stock (taking into account the stock from the previous week, orders placed for that raw material, and planned deliveries).

$$STR_{r,t} = STR_{r,t-1} + E0_{r,t} + E_{r,t} - (1 + \%scrap_r) \sum_{o \in O} \sum_{k \in K} \sum_{v \in V} \left(\sum_{lf \in Lf} \frac{ynf_{r,k,v}}{1000} \times xk_{o,k,lf,t,v} + pv_{o,k,v,t} \times yf_{r,k,v} \right), \quad r \in R, t \in T \text{ with } t \neq 1 \tag{66}$$

Specifically, the initial stock of raw materials at the beginning of the first period is constrained to the designated raw material's initial stock.

$$STR_{r,t-1} = stkr0_r, \quad r \in R, \;\; t = 1 \tag{67}$$

The last constraint regarding raw materials is responsible for ensuring the correct execution of the raw materials ordering process by restricting the possibility of placing an order available for a specific raw material before the agreed lead time.

$$E_{r,t} = 0, \quad r \in R, \;\; t \leq lt_r \tag{68}$$

BOM Recipes

The implementation of the concept of BOM recipes involves the application of three constraints related to three distinct topics. Firstly, is required to incorporate a constraint responsible for ensuring the allocation of the initial stock of each product ($sti_{o,k}$) to the various existing recipes, resulting in the initial stock of the product using a particular recipe ($STKiv_{o,k,v}$).

$$\sum_{v \in V} STKiv_{o,k,v} = sti_{o,k}, \quad o \in O, k \in K \tag{69}$$

Secondly, in order to ensure conformity in the units of each order, it has been established that an order can only contain products manufactured using the same recipe.

$$\sum_{v \in V} pv_{o,k,v,t} \leq 1, \quad o \in O, k \in K, t \in T \tag{70}$$

The ultimate constraint within the set of BOM recipe constraints, as presented below, ensures and enforces the activation of the binary variable $pv_{o,k,v,t}$, which indicates whether a specific product recipe is used in its production, in a given planning week.

$$\sum_{lf \in Lf} xk_{o,k,lf,t,v} \leq M \times pv_{o,k,v,t}, \quad o \in O, k \in K, t \in T, v \in V \tag{71}$$

At last, concluding this section, the following constraints guarantee the accurate definition and adherence to the domain of all decision variables within the formulated optimization model. These constraints classify the variables into real, integer, and binary categories, ensuring their proper specification and inclusion within the model.

$$Er_{r,t}, \; STR_{r,t} \in \mathbb{R}_0^+ \tag{72}$$

$$\begin{gathered} xk_{o,k,lf,t,v},\ hr_{f,lf,t},\ Dl_o,\ hn_{f,lf,t},\ he_{f,lf,t}, \in \mathbb{N}_0 \\ nINI_{f,lf,t},\ nDAP_{f,lf,t},\ nDA_{f,lf,t},\ nDP_{f,lf,t},\ nAP_{f,lf,t},\ nD_{f,lf,t},\ nA_{f,lf,t},\ nP_{f,lf,t} \in \mathbb{N}_0 \\ nK_{f,lf,t},\ d_{d,f,lf,t},\ p_{p,f,lf,t},\ a_{a,f,lf,t},\ STK_{o,k,t,wh,v},\ STKiv_{o,k,v} \in \mathbb{N}_0 \end{gathered} \tag{73}$$

$$\begin{gathered} pp_{k,lf,t},\ ppbm_{o,k,lf,t},\ pv_{o,k,v,t},\ ff_{c,t},\ q_{o,t},\ ns_o,\ alf_{f,lf,t} \in \{0,1\} \\ whe_t,\ ws_{h,f,t},\ ws\_line_{h,f,lf,t},\ vn_{f,lf,t},\ ve_{f,lf,t} \in \{0,1\} \end{gathered} \tag{74}$$

4.4. Interface

The interactive interface file serves as a vital complement to the model, encompassing a comprehensive array of inputs that are subject to parameterization by the planning team. Beyond its foundational role in providing data, the interface file assumes an even more dynamic character. It empowers the alteration and customization of the model's output plan, accommodating specific scenarios and exceptions, all with the overarching objective of ensuring a seamlessly aligned plan that impeccably adheres to the currently prevailing operational constraints and requirements. To ensure the correct operational effectiveness of the interface and the presence of the most current information, it is essential that the file undergo updates on a weekly basis at the commencement of each week, or whenever modifications occur in the planning conditions.

The interface is partitioned into three fundamental sections, as depicted in Figure 26, which serves as an illustrative representation of the menu sheet. The initial section encompasses a comprehensive array of global inputs, encompassing not only inputs relevant to the model but also its specific parameters. Additionally, it includes parameters that hold significance for both factories collectively, such as OEE values and overarching cost factors. The subsequent section comprises parameters distinctive to each factory, including the working schedules of individual filling lines, planned downtimes, exceptions, and directives for implementing adjustments in the model's plan output. A comprehensive illustration of these sections is presented in Appendix A.

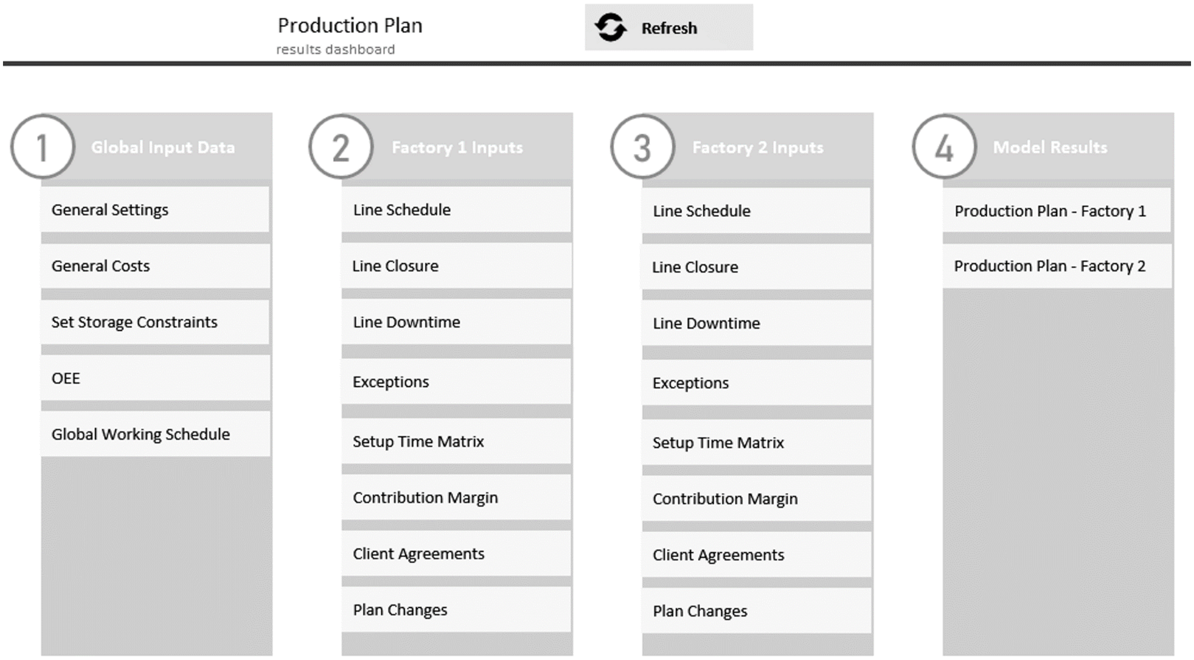

Figure 26: Interface Menu

Thus, the interface facilitates the configuration of numerous inputs, which, in combination with the data sourced from SAP, form the complete set of inputs for the optimization model. Table 5 encompasses all the interface-specified inputs, accompanied by corresponding descriptions.

Table 5: Optimization model's inputs parameterized in the Interface

Input	**Description**
Factory	The factory for which the production plan is intended.
Filling Line	The factory filling line for which the production plan is being generated.
Model's General Inputs	Data regarding model's parameters, such as the run time and if it is desired to download new data from SAP.
General Costs	Expenses related to the production in each filling line, workforce costs, scrap percentage, and other related factors that need to be taken into account.
Initial Factory's Working Schedule	The working schedule that each factory should operate in the first weeks of planning.
Global Working Schedule	All the possible working schedules in each factory, as well as the regular, night and overtime hours associated.
OEE	OEE values, without considering the setups, in each filling line.

Line Schedule	Upcoming four-week operational schedule for each filling line.
Line Closure	Unfeasible working schedules for each filling line across the 17 weeks of planning.
Line Downtime	Planned downtime in regular, night and overtime for each filling line.
Below MOQ	Product codes and weeks within the planning horizon where production below the MOQ is permissible.
Production Different than Forecast	Product codes and weeks within the plan requiring production quantities different from the originally forecasted amounts.
Material Replacement	Production orders (specific product within a particular planning week) involving material substitution, including details about the previous and replacement component codes.
Line Impossibilities	Product attributes that, despite the presence of the filling line in the designated process routes, cannot be manufactured due to tool shortages and other constraints.
Quarantine	Identification of products along with their respective quarantine durations.
Below MPR	Family designation and weeks within the plan where production below the MPR is allowed.
Setup Time	Duration taken for each type of setup on every filling line.
Contribution Margin	Cost associated to the cancellation of an order of a specific customer.
Client Agreement	Fixed and binding period, in weeks, of each technology of a specific customer.
Plan Changes	Modifications (additions, deletes, or replacements of productions) to be integrated into the finalized output plan.

4.5. Dashboard

To facilitate the planning team's analysis of the generated plans, a *Power BI* dashboard has been meticulously crafted. This dashboard hosts an array of visuals, designed to streamline the task of analyzing and monitoring production KPIs. Beyond offering stakeholders real-time insight into KPIs, the dashboard acts as a powerful tool delve into the characteristics of the generated production plan. Through a fusion of data visualization and advanced analytical capabilities, this dashboard presents a holistic platform for evaluating plan effectiveness and making well-informed decisions. It facilitates scenario comparisons and allows for a comprehensive assessment of production plans, thereby empowering better decision-making.

The developed dashboard serves as a comprehensive repository containing visuals for the evaluation and assessment of a production plan. Furthermore, it offers the capability to selectively filter various variables based on the specific visual under evaluation, such as factory, filling line, product type, among others. The dashboard is structured with multiple distinct views. The initial view provides an overarching perspective, enabling a cursory examination of the plan and validation of global data. Subsequently, a detailed view facilitates a more intricate analysis, allowing for a meticulous assessment of the production plan and related metrics at the level of individual orders. Additionally, the dashboard comprises dedicated views focused on capacity, production, orders, costs, raw materials, and setups. These specific views contain a concentrated set of analyses and visuals pertinent to each respective area. The purpose of these views is to enable in-depth assessment of specific topics when required, without the necessity to navigate through unrelated metrics. Lastly, the dashboard includes a comparison view designed to facilitate the assessment of two generated plans, allowing for a comparison of the KPIs. The mentioned views are showcased in detail in Appendix B.

5. Results

This chapter provides a overview of the experimental results derived from the implementation of the methodology discussed in Chapter 4. The primary objective is to shed light on the initial results yielded by the generated plans and to assess the computational performance. By conducting this study in real-world manufacturing environments, valuable insights are gathered regarding the effectiveness of the proposed methodology. The experimental phase involved deploying the optimization model within the production systems of both factories, allowing the generation of optimized production plans.

Through the implementation of a thorough examination of the acquired results, this chapter delves into the key findings and highlights the improvements achieved in terms of production planning efficiency and performance. It evaluates the extent to which the generated plans adhere to the predetermined objectives and facilitate the most effective use of resources, achieved through visual representation of data through graphs and the analysis of results monitored in the implemented dashboard. Moreover, the chapter assesses the computational performance of the implemented approach, examining factors such as the execution time and the adaptability of the optimization model.

5.1. Production Planning Results

The plans generated were carefully developed, taking into account various important factors. These factors encompassed the demand for each product, the available production capacity, the availability of raw materials, and the associated lead times. The objective was to align these elements, achieving a balance between meeting customer demand and ensuring streamlined production operations.

Besides minimizing a cost function, the model aimed to achieve balanced production volumes and efficient allocation of resources. To absorb the impact of demand peaks, the concept of safe quantity was incorporated, allowing for production in advance, based on customer reliability.

A *Power BI* dashboard was created to analyze the generated plans, allowing for a comprehensive examination of the findings presented in this section. This dashboard served as a valuable tool for extracting insights and drawing meaningful conclusions from the data. By leveraging the interactive features and visualizations offered by *Power BI*, a detailed exploration of the plans was made possible, enabling a deeper understanding of their implications and outcomes.

In the following sections, the optimized plans for both Factory 1 and Factory 2 are presented and compared with the production plan created by the planning team. To allow the comparison between the current and the optimized plan, the optimization model examined the plan devised by the planning team. This involved setting and limit fixed production quantities and weeks for each order. By doing so, both plans underwent identical data processing and production constraints. Consequently, it became feasible to calculate the values of the same KPIs and conduct a meaningful comparison.

Given the substantial differences in size and operational approaches - *modus operandi* - between these factories, it is crucial to examine their results individually. This approach ensures a clear and comprehensive understanding of the outcomes by effectively highlighting the unique characteristics and challenges faced by each factory.

5.1.1. Optimized Production Plan for Factory 1 - Comparison of Results

To ensure efficient production management at Factory 1, a comprehensive production plan was formulated. The primary objective of this plan was to allocate the demanded quantities effectively among the different production lines illustrated in Figure 9, over a span of 17 planning weeks.

In this section, the elaborated dashboard is leveraged to present a comprehensive analysis of the results obtained for Factory 1. The focus remains on utilizing graphics to provide valuable insights into the outcomes of the production planning process. Furthermore, includes a comparison of the results with the company's planning team's strategy for the same time horizon.

Orders' Status

This plan incorporates a total of 2215 orders, pertaining to 822 products from 18 customers, to be produced in the 16 filling lines. Upon comparison with the plan formulated by the planning team, noteworthy variances were identified in terms of the number of anticipated, delayed, and canceled orders. It is important to highlight that the focus is on the first four weeks of planning. These weeks correspond to the forthcoming month and constitute a pivotal period for plan accuracy, owing to the necessity of confirming orders to the customers. The results are presented in the graph of Figure 27.

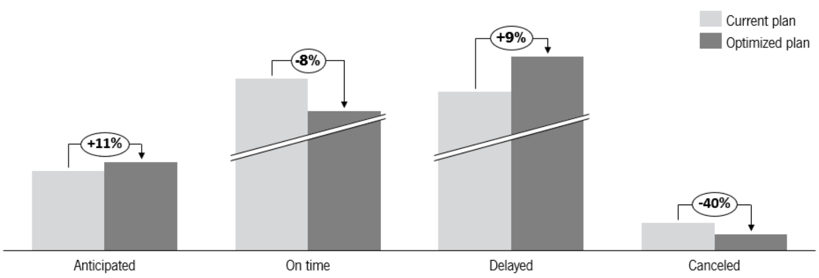

Figure 27: Orders' status for Factory 1

By analyzing the Figure 27, it becomes evident that the optimized production plan yields notable outcomes. Firstly, it is worth noting that anticipated orders refer to orders that were completely fulfilled before the scheduled deadline. Therefore, the 11% increase in anticipated orders observed in Factory 1, rises to 17% when considering orders that were partially anticipated. As previously mentioned, Factory 1 contends with capacity constraints, which pose challenges to the implementation of the safe quantity concept, thus underscoring a noteworthy milestone attained.

Additionally, it is important to emphasize the 40% reduction in canceled orders, contributing to enhance customer satisfaction. Nevertheless, this decrease comes with drawbacks, such as a 9% increase in delayed orders. However, the average delay duration in the optimized plan has decreased from 5.33 weeks to 4.61 weeks. This indicates that the optimizer prioritizes minimizing delays across a larger number of orders, rather than incurring lengthy delays for specific customer orders.

The dashboard provides visibility regarding the factors that lead to cancellations. These factors can be categorized into orders that fall below the MOQ, orders that do not align with the MPR, insufficient availability of raw materials, product-related statuses that prevent their production, and instances involving opportunity costs. This information can be utilized to identify potential cases as exceptions or to improve management of raw material procurement and delivery. The opportunity cost category encompasses reasons such as insufficient capacity, cases where cancellation is more cost-effective, or situations where an optimal solution could not be found. Table 6 provides an analysis of the number of canceled orders of the two plans, taking into account the reasons discussed.

Table 6: Reasons of unfulfilled orders of Factory 1

	Current plan	**Optimized plan**
Below MOQ	8	6
Below MPR	5	4
Not enough raw materials	7	2
Opportunity cost	0	0

Examining the table, it is evident that the distinguishing cancellation factors are associated with three issues: production falling below the MOQ or MPR, and lack of raw materials. These specific orders underwent detailed analysis. The optimization model was capable of producing these orders by anticipating future orders through the implementation of the safe quantity concept, complying with the MOQ or MPR. Furthermore, regarding the cancellations' decrease due to insufficient components, the model was able to improve raw material management, leading to a reduction in cancellations.

Nonetheless, the model cannot replicate the *ad-hoc* decision-making of the planning team. In instances where both plans indicate quantities below the MOQ or MPR, the planner might have authorized the production of these orders, as exceptions, or asked for a revision of said quantities. Similarly, when there is lack of raw materials, the planner might proceed with production based on pending deliveries, a situation that is not accommodated in this analysis. Even so, these results highlight superior decision-making by the model, minimizing overall cancellations under the same data and constraints. The planning team can then use the interface to revise these orders and further improve the model.

Production Costs

Considering optimizer's decisions in assigning production orders to different filling lines, it was possible to determine the cost linked to the optimized plan over the entire planning horizon. The overall cost function encompasses warehousing and holding costs, factory opening and operational costs, workforce costs, and costs associated with order delays or cancellations. It is important to note that the costs related to delays or cancellations are artificially inflated and, consequently, not analyzed. These fictional values are used to guarantee that the optimizer consistently meets customer deadlines, except in unavoidable constraints. The comparison between the cost function value obtained for the optimized plan and the plan developed by the planning team can be observed in the graph depicted in Figure 28.

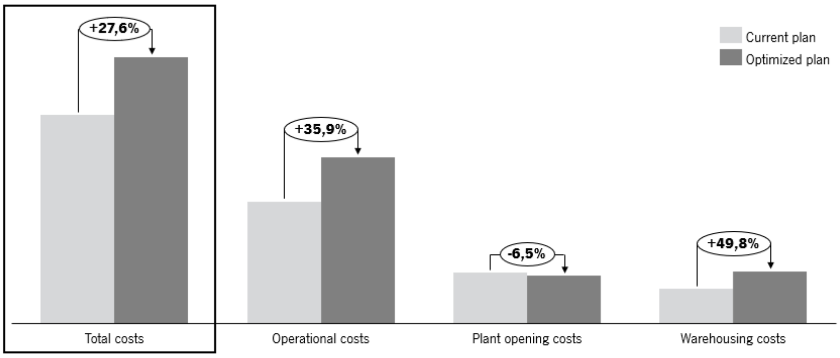

Figure 28: Production costs for Factory 1

The graph illustrates a rise in operational and warehousing costs, accompanied by a decrease in plant opening expenses, when comparing optimized and current plans. Firstly, the higher warehousing costs stem from storing anticipated quantities until order production is finished, a result of implementing safe quantity concept. Secondly, operational costs, covering filling line usage and workforce expenses, increase because the model strives to fully utilize filling lines, prioritizing faster yet more expensive lines. This approach incurs in expenses related to night and overtime hours. Lastly, and conversely, reduced plant opening costs arise from shorter factory working hours during the planning weeks.

As highlighted, the optimized plan leads to an increase of 27.6% in the overall costs. However, this increase is related to a considerable rise in the total volume produced. Thus, it is required to evaluate the cost on a per-unit basis - unitary cost -, in order to get a more complete picture (Figure 29).

Examining this unitary cost reveals an interesting finding: as compared to the current plan, the optimized plan results in a 3.4% reduction of this metric. The reduction verified suggests that the model is a useful asset for the organization from a purely economic perspective. Although the total cost has increased, it is important to recognize that this increase is the result of a purposeful choice to boost production. The plan's ability to produce goods at a cheaper cost per unit is highlighted by the decrease in unitary cost, which might improve the company's long-term profitability and competitiveness.

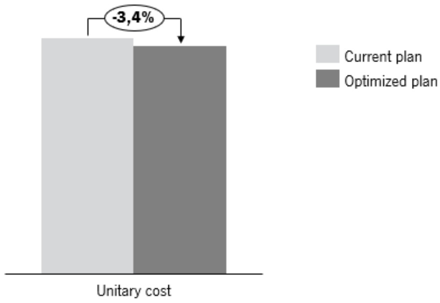

Figure 29: Unitary production costs for Factory 1

Quantity Produced

Another KPI to consider pertains to the quantity of finished goods produced during each week of the planning period. In this way, focus on the volume of finished goods manufactured is necessary to assess Factory 1's performance. Figure 30 visually represents the production quantity trends for both the plan created by the planning team and the optimized plan in the first eight weeks of planning.

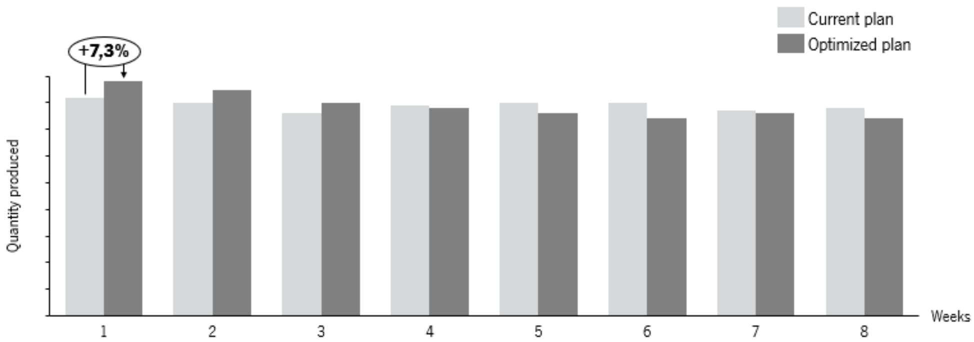

Figure 30: Quantity produced in Factory 1

From looking at the graph, it is clear that both plans show a comparable distribution of the quantity produced across the time horizon. Furthermore, the two plans exhibit a residual surge in production in the first week. This increase can be attributed to the backlog of pending orders that require fulfillment in the initial weeks, to minimize the overall costs. Specifically, during the first week, the optimizer's allocation of orders leads to a 7.3% increase in the quantity of units produced, and this aligns with the reduced number of order cancellations during that timeframe. Nonetheless, the optimization approach and the planning team's strategy over the eight-week duration is distinct. The planning team aims for a balanced production throughout the time frame, while the optimizer shows a downward trend over time. In the first weeks, the optimizer generated higher quantities in order to utilize the most the scheduled work hours. In the following weeks, the suggested production decreases.

In addition, it is worth mentioning that Factory 1's application of safe quantity has a limited impact due to most filling lines being constrained by capacity. However, given the 11% rise in anticipated orders evident in Figure 27, it can be inferred that the optimizer attempt to fulfil their demands during the initial weeks by anticipating certain orders and maximizing the use of filling lines unaffected by capacity constraints.

Working Schedules

In order to undertake an analysis that transcends purely economic aspects, it is important to assess the most efficient working schedules for each line and the factory across the 17-week planning period. These schedules were designed to ensure strict adherence to all predefined constraints. This detailed scheduling method optimizes resources and aligns production plans with the factory's capacity, ensuring efficiency and meeting customer demands proficiently. The outcomes of this process are presented in Table 7. It's worth emphasizing that the factory's working schedules were established by considering the highest capacity utilized by any production line during each week of the planning phase.

Table 7: Factories' working schedules for Factory 1

	Current plan	**Optimized plan**
1st to 4th weeks	24/7	24/7
5th to 8th weeks	24/7	24/7
9th to 12th weeks	24/7	24/5 + 2 shifts

Upon scrutinizing the working schedules of Factory 1, it becomes evident the capacity reduction during the third period, resulting in a decrease of four extra shifts. This can be achieved by the implementation of optimized order allocation and the safe quantity. Considering that the working schedules for the initial weeks are pre-established, the optimizer is constrained to operate within these timeframes.

Furthermore, it is important to note that certain production lines, particularly the aerosol lines, operate at full capacity, exerting a significant influence on the factory's working schedule. Consequently, there is limited scope to gauge the precise impact of the optimization model on Factory 1's capacity during the initial weeks, as these schedules are essentially dictated by the high-demand lines.

Hence, the working schedules assigned to each filling line is a pivotal metric. As the line schedules for the initial weeks are preordained by the planning team, no divergence is observed in this metric. Consequently, the focus of analysis must shift towards the working schedules meticulously selected by the optimizer for the fifth through eighth weeks and conduct a comparative assessment with the current plan. These line schedules are meticulously documented in Table 8.

Table 8: Working schedules of Factory 1's filling lines from 5th to 8th weeks

	Current plan	**Optimized plan**
LA01	8/5	8/5
LA02	24/5 + 2 shifts	24/7
LA03	24/7	24/7
LA04	24/5 + 2 shifts	24/5
LA06	16/5	16/3
LA07	24/5	16/5
LA08	16/5	16/4
LA09	16/3	16/5
LL01	16/5	16/5 - 1 shift
LL02	0/0	0/0
LL04	8/5	8/5
LL05	8/5	8/4
LL06	24/5	24/5
LL08	24/5	18/5
LL09	0/0	0/0
LL10	18/5	24/5

Upon comparing the results, notable disparities become apparent due to different orders allocation. Firstly, it is important to highlight that the filling line LA01 is dedicated to one customer, allocating a small percentage of the total products. Therefore, the plan for this line is very similar in both plans, since the plan basically consists in producing the demand of each week.

Furthermore, it is worth noting to highlight the excessive utilization of aerosol lines at the expense of the liquid lines. Lines LA02 and LA04, which are extensively utilized, present contrasting behaviors. The optimizer managed to reduce the working schedule of line LA04 by two shifts, optimizing its efficiency. However, this should be considered alongside the line LA02, where the model selected a schedule of 24/7, utilizing the entire capacity. This decision is based on its higher throughput, allowing to maximize its capacity for smoother operations. A similar pattern is observed with lines LL08 and LL10.

In the other lines, there are slight reductions in the working schedule in the optimized plan. This can be attributed to the safe quantity concept, where the model suggests the early completion of orders within the first four weeks. As a result, the working hours for the upcoming weeks can be scaled down.

Filling Lines' Capacity

Considering the working schedules selected for each production line, it is key to assess the capacity used. The graphs depicted in Figure 31 highlights the disparity in lines' utilization for the first four planning weeks, between the optimized plan and the capacity allocation in the plan created by the planning team. This measurement takes into consideration the total hours utilized in each filling line, encompassing production time, setup time, and downtimes.

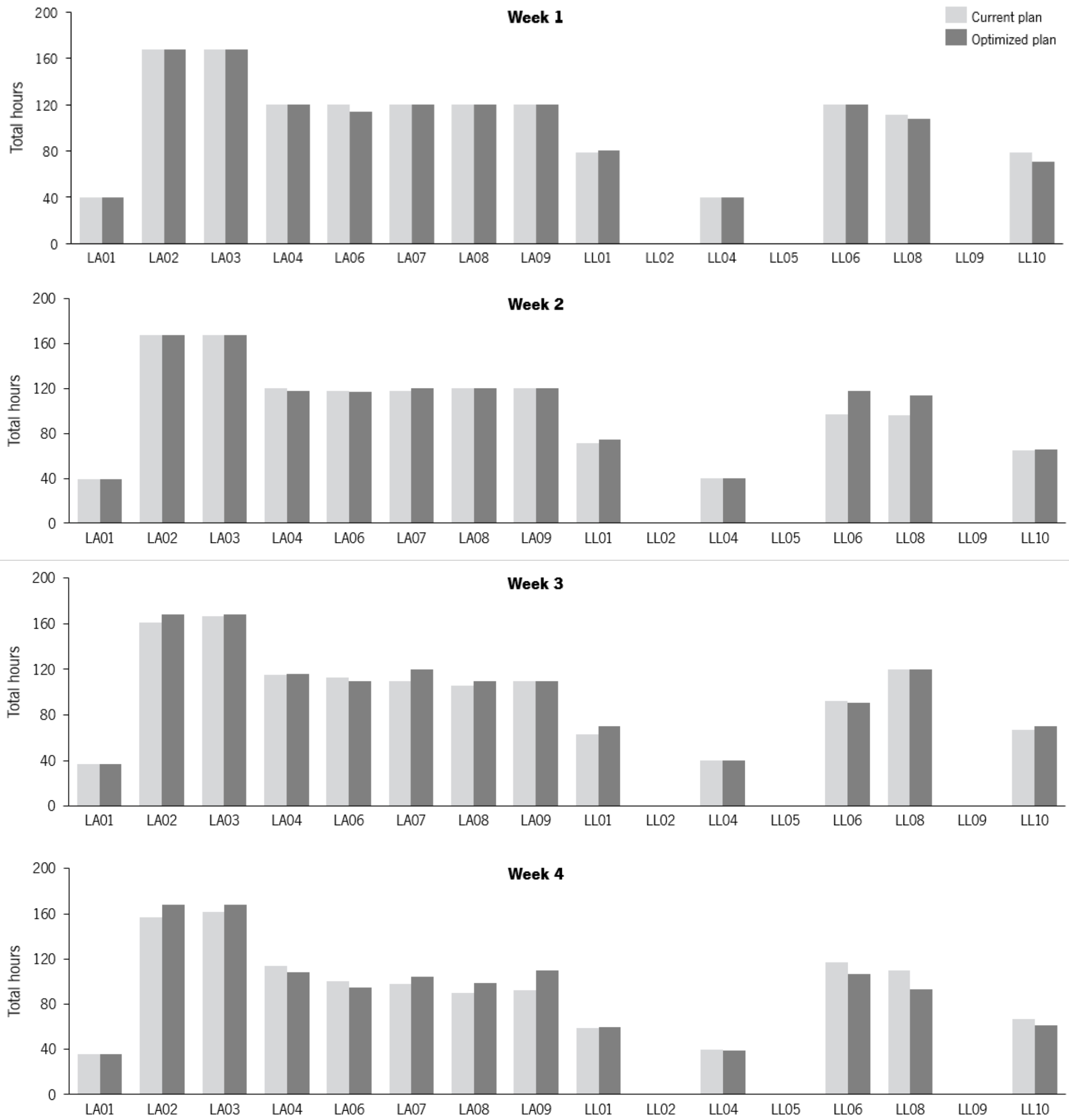

Figure 31: Filling lines' capacity of Factory 1 for the first four weeks

The analysis of Figure 31 indicates that in the initial week, both the current and optimized plans maximized the available line capacity to meet the backlog orders and first-week demand. In the subsequent week, specifically in the liquid lines, the current plan aimed to fulfill weekly demands, utilizing slightly less capacity. In contrast, the optimizer utilized fixed schedules to their fullest, anticipating future orders. During weeks 3 and 4, there are noticeable differences in the total allocated hours between the two plans. This can be attributed to two primary factors: the rise in anticipations during the initial four weeks, leading to a higher total quantity produced, and the planning team's decision to allocate production among preferred lines, whereas the optimizer favours faster lines.

Production and Setup Time

The allocation of time between actual production and setup activities is an additional significant metric to consider. A setup involves the time needed to prepare production lines and machinery for initiating the manufacturing of a new product. The proportion of time dedicated to producing finished goods and the proportion of time allocated to setup, over the entire planning horizon, can be observed in the graph presented in Figure 32, for both plans under study.

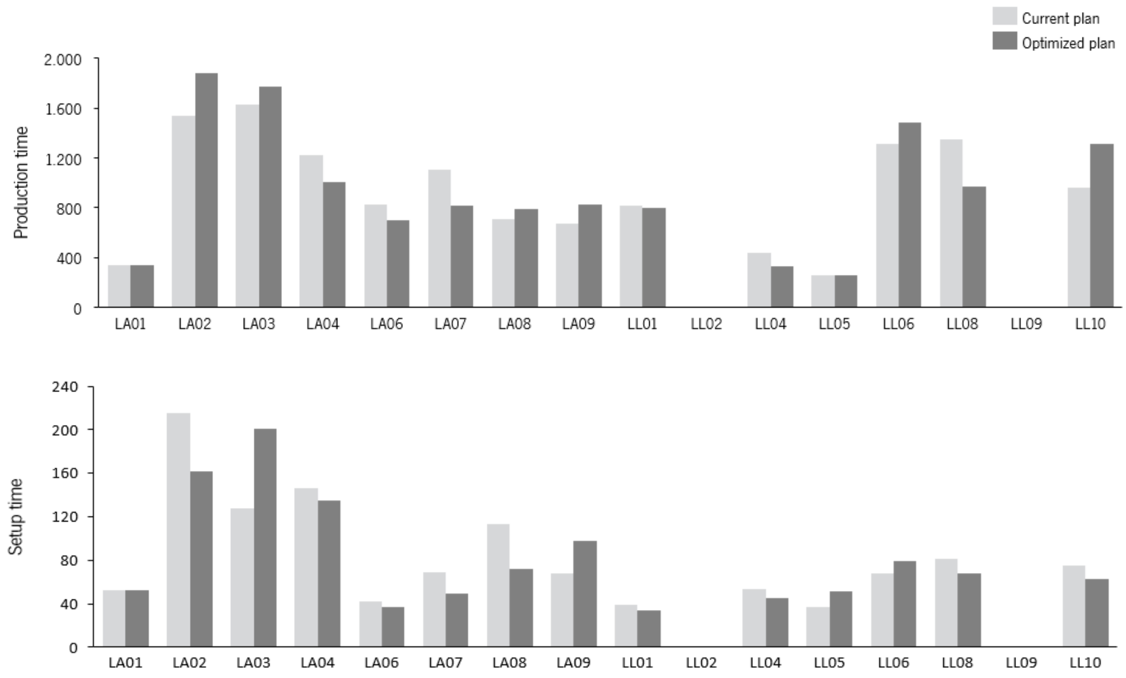

Figure 32: Production and setup time in Factory 1

When comparing the two examined plans, it becomes apparent that they exhibit a considerable degree of resemblance. In general, the optimizer dedicates more time to production, which is directly connected to the increase in the finished goods' production. Additionally, it is noticeable that while the planning team attempts to evenly distribute production across all filling lines, the optimizer prioritizes meeting the demands of lines with higher throughput.

By focusing on the production and setup times of both plans, it is clear that in the specific cases of filling lines LA02 and LL10, they have more time allocated to production and less time allocated to setup in comparison to the current plan. This adjustment is a result of the optimizer directing more significant production volumes to these lines to ensure smooth and efficient production operations. However, the opposite case also occurs, as is evident with LA03. In this line, the optimizer allocates more time to production but also significantly increases setup time. This is directly related to the production of smaller orders, which require more frequent changeovers.

5.1.2. Optimized Production Plan for Factory 2 - Comparison of Results

To ensure efficient production management at Factory 2, a comprehensive production plan was also developed. The underlying rationale of this plan remained consistent with Factory 1, aiming to effectively allocate the demanded quantities across the various production lines specified in Figure 10.

The purpose of this section is similar to the previous one. However, the focus now shifts to Factory 2, where the plan also spanned 17 weeks and shared the objective of optimizing resource utilization and meeting customer demands. This section encompasses the results obtained for Factory 2 and presents relevant graphical representations sourced from the elaborated dashboard. Additionally, mirroring the methodology employed for Factory 1, an analogous comparative analysis is undertaken between these outcomes and the production plan devised by the company's planning team.

Orders' Status

This production plan encompasses a set of 578 orders belonging to 203 distinct products, all attributed to 20 different customers. By contrasting it with the plan developed by the planning team, significant differences were observed in the number of anticipated, delayed, or canceled orders. A similar analysis was conducted for Factory 2, and the corresponding results are presented in Figure 33.

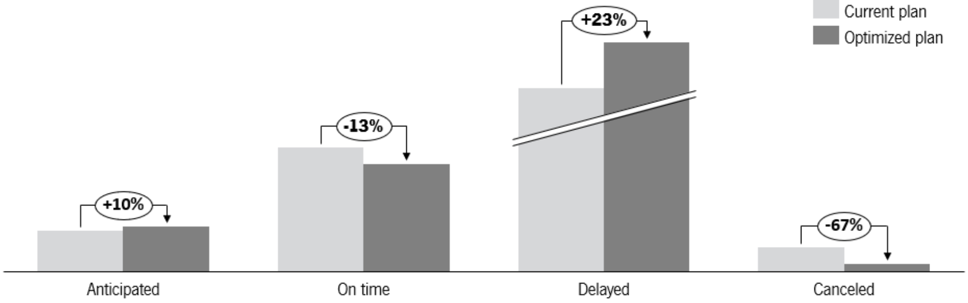

Figure 33: Orders' status for Factory 2

Upon careful analysis of the graph, it becomes evident that the production plan generated by the optimization module yield significant outcomes for Factory 2, during the initial four weeks. Notably, there is a 10% increase in the number of orders that were fully anticipated. This emphasizes an enhanced proactive approach to meeting customer demands.

Furthermore, it is worth highlighting a 67% decrease in the number of canceled orders, thus improving order stability and overall performance. Conversely, there was a 23% increase in the number of delayed orders. It is important to note that the average duration of delays in the optimized plan has decreased from 4.57 to 4.08 weeks when compared to the current plan. In addition, it is pertinent to mention that a certain increase in order delays was predicted, given the reduction in order cancellations. Moreover, the reduction in the weeks of delay contributes to enhance customer satisfaction.

Factory 2 benefits from the same comprehensive dashboard as Factory 1, which enhances visibility into the factors leading to production order cancellations. These factors can be categorized into the same main groups. Table 9 presents a comparison of the number of canceled orders between the two production plans, taking into account the aforementioned reasons.

Table 9: Reasons of unfulfilled orders of Factory 2

	Current plan	**Optimized plan**
Below MOQ	1	1
Below MPR	0	1
Not enough raw materials	11	2
Opportunity cost	0	0

Upon reviewing the table, it becomes apparent that the differentiating factors regarding order cancellations within the initial four weeks pertain to two specific issues: production falling below the MPR and shortage of raw materials. Firstly, within the optimized plan, we observe one additional order cancellation due to the failure to meet the MPR. This arises from the model's decision to forgo producing the entire product family, opting instead to prioritize the production of another order with a higher associated cancellation cost. Furthermore, in relation to the difference of nine order cancellations documented in the current plan resulting from insufficient raw materials, it is evident that the optimization process facilitates more effective raw material management, consequently reducing cancellations.

Nevertheless, similar to Factory 1, the optimizer cannot replicate the *ad-hoc* decision-making of the planning team. Therefore, both the current and optimized plans may include more cancellations than those that are genuinely impossible to produce, considering specific exceptions that depend on planners decisions. Once again, the difference in the number of cancellations highlights the potential of the model to aggregate certain orders and manage raw materials, ultimately reducing cancellations.

Production Costs

Taking into account the same criteria mentioned earlier, which include optimizer's decisions for production order allocation, the associated cost of the plan implemented for Factory 2 was determined. Once again, the delay and cancellation costs are fictitious, and, therefore, are not considered in the analysis. The comparison between the cost function values for the optimized plan and the plan devised by the planning team can be observed in the relevant graph - Figure 34.

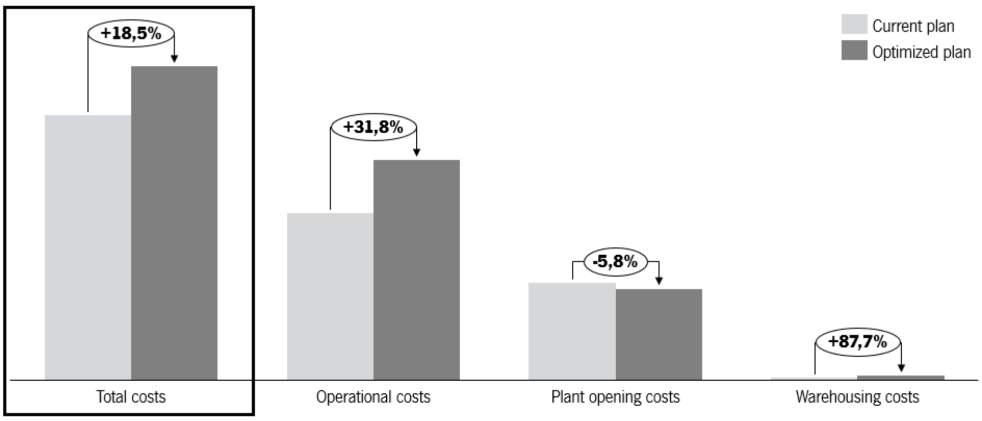

Figure 34: Production costs for Factory 2

The graph demonstrates an increase in operational and warehousing expenses, coupled with a reduction in plant opening costs when comparing the optimized and current plans. Firstly, operational expenses, rise because the model aims to maximize filling line usage, favoring faster but more costly lines, since it provides higher throughput to satisfy more deliveries on time. Secondly, elevated warehousing costs result from implementing the safe quantity concept. Lastly, reduced plant opening costs occur due to shorter factory working hours in the planning weeks.

As emphasized, adopting the optimized plan results in an 18.5% rise in overall expenses. Yet, this increase is directly tied to a substantial boost in the total production volume. Assessing the unitary cost is required for a comprehensive understanding (see Figure 35).

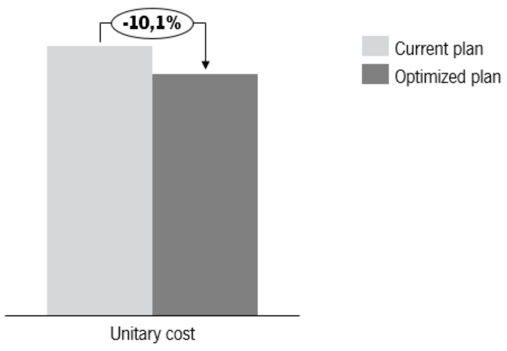

Figure 35: Unitary production costs for Factory 2

Analyzing the per-unit cost demonstrates a 10.1% decrease associated to the optimized plan, indicating its economic value for the organization. Despite the overall cost increase, it is important to acknowledge that this rise is linked to enhancing production. The plan's efficiency in producing goods at a lower per-unit cost underscores its potential to enhance the company's long-term productivity.

Quantity Produced

In order to analyze the production performance of Factory 2, the quantity of finished goods produced during the first eight weeks is a relevant metric. Figure 36 presents a graph that illustrates the overall trend in production quantity for both the plan devised by the planning team and the optimized plan.

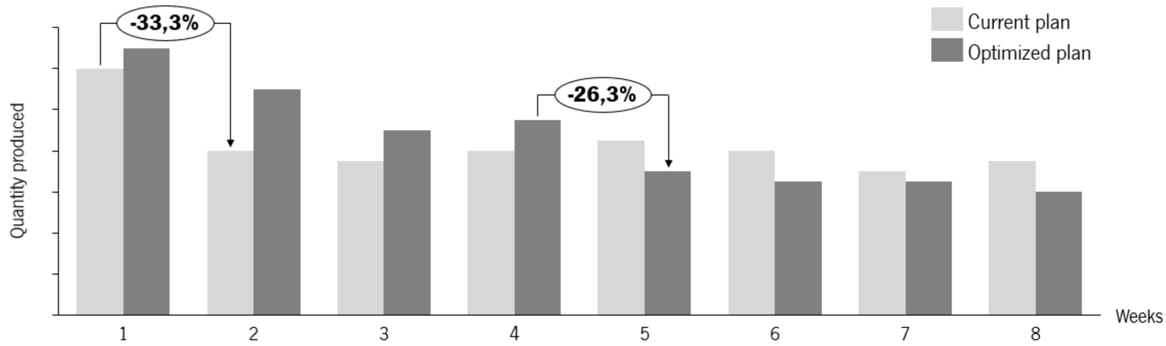

Figure 36: Quantity produced in Factory 2

Upon a thorough analysis of the graph, it becomes evident that both plans exhibit a upsurge in production during the initial week. This increase can be attributed to prioritizing backlog orders and optimizing cost-efficiency by concentrating production efforts in the early weeks. Nevertheless, due to a lower number of canceled orders, the optimized plan manages to produce a slightly higher quantity.

Furthermore, in the current plan, there is a pronounced decrease of 33.3% in the quantity produced from the first week to the second. In the subsequent weeks, the quantity remains relatively consistent. However, the optimization model makes a different strategic choice. Owing to the necessity of maintaining an unaltered working schedule in the initial weeks, the model proposes an increase in production during this period. This approach can only by anticipating some orders to the initial weeks and utilize the production capacity to its fullest extent, leading to reduced volumes in the upcoming weeks.

Working Schedules

In order to conduct a similar non-pure economic analysis for Factory 2, the model established the optimal working schedules for each filling line and the overall factory over the 17-week planning period. These schedules were meticulously chosen to guarantee compliance with all specified constraints. The resulting outcomes are showcased in Table 10. The factory's working schedule are determined based on the maximum capacity utilized by one of the lines during each week.

Table 10: Factories' working schedules for Factory 2

	Current plan	**Optimized plan**
1st to 4th weeks	16/5	16/5
5th to 8th weeks	19.5/5	18/5
9th to 12th weeks	16/5	16/4 - 1 shift

The examination of Table 10 elucidates that the implementation of optimized order allocation and the incorporation of the safe quantity concept results in a decrease in Factory 2's capacity during the second and third periods, when the working schedules are not predetermined. However, Factory 2's overcapacity enables a reduction in active working schedules during the subsequent planning periods.

An additional metric to consider involves the examination of the specific working schedules designated for each filling line. Given that the line schedules for the initial weeks are parameterized by the planning team, no disparity exists in this metric. Hence, it is pertinent to direct our attention to the working schedules chosen by the optimizer from the fifth to the eighth week and make a comparative analysis against the current plan. This data is detailed in Table 11.

Table 11: Working schedules of Factory 2's filling lines from 5th to 8th weeks

	Current plan	Optimized plan
A1	16/4	16/3
A2	19.5/5	16/5
A3	8/4	8/3
A4	16/3	16/5
A5	16/4	18/5
A6	8/1	0/0
L1	8/3	8/3
L2	0/0	0/0
Copacking	8/3	8/2

Upon comparing the results, disparities become apparent due to different orders allocation. Firstly, it is important to highlight that in the current plan, the most utilized line is A2, operating at a capacity of 19.5/5, whereas the optimizer favors the utilization of line A5, operating at 18/5. This fact can be justified by the optimizer's preference for filling lines with higher throughput, even if the cost is higher. Moreover, it is possible to deduce that due to the reduced number of lines dedicated to liquids, the optimizer does not have much flexibility to alter the schedule of liquid lines. Conversely, when considering the aerosol lines, it is possible to allocate products differently and adjust the working schedule in a manner that is more cost-effective.

Filling Lines' Capacity

Considering the chosen schedules for each filling line, is required to evaluate lines' capacity. Figure 37 shows line utilization in the first four weeks, comparing the optimized and planning team's plans. This measure accounts for total hours used in each filling line, including production, setup, and downtime.

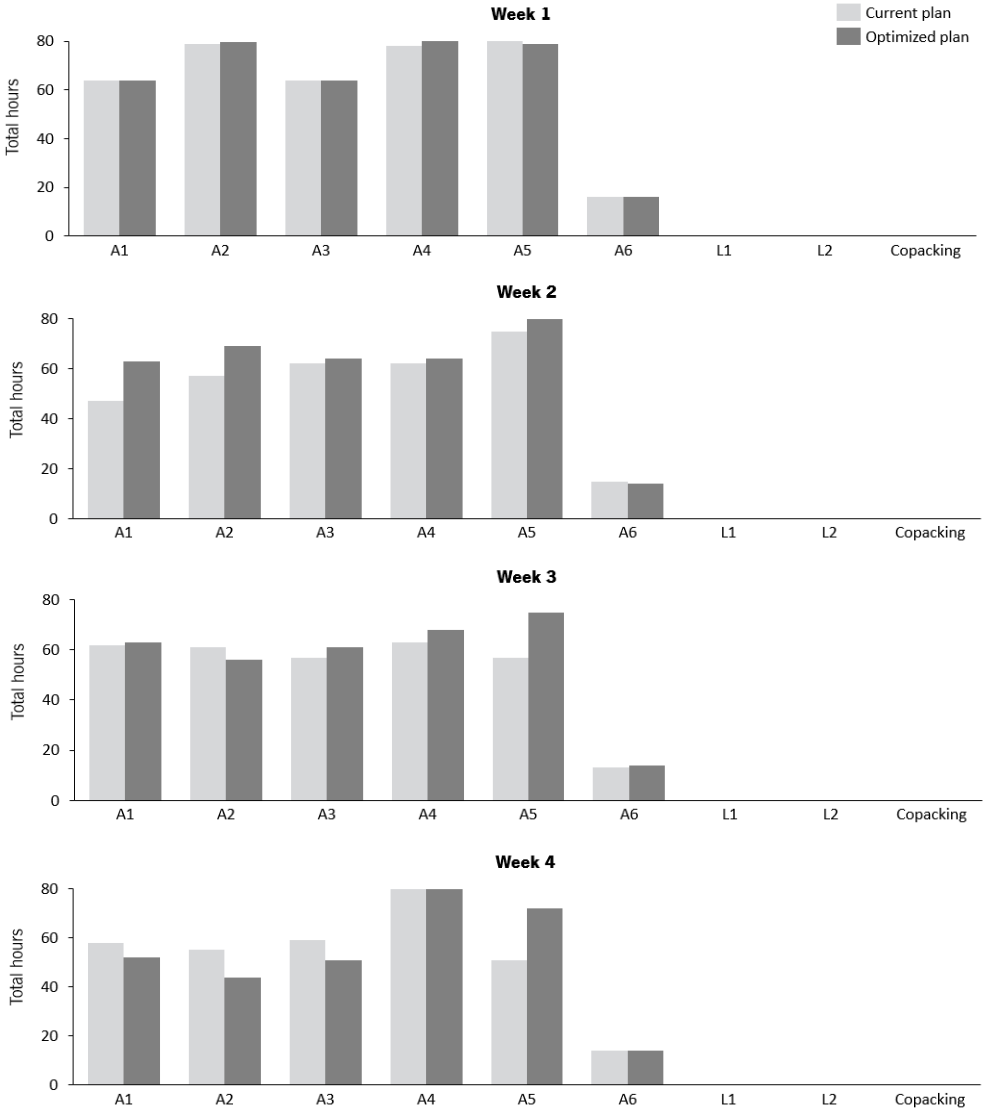

Figure 37: Filling lines' capacity of Factory 2 for the first four weeks

Figure 37 reveals that in the initial week, both plans utilized maximum line capacity to fulfill backlog orders and demand pertaining to the first week. In the following weeks, significant differences in allocated hours between the plans emerge, and, specifically in the fourth week, order allocation diverges markedly. This situation arises because the company, currently, operates by assigning specific customers to particular filling lines. Consequently, the planning team prefers lines A1, A2, and A3, allocating products to the preferred lines. In contrast, the optimizer gives priority to the fullest line, A5, which has the highest throughput. Notably, line A6 maintains consistent capacity in both plans, considering its future closure and minimal demand. Additionally, in week 4, line A4 is dedicated to out-of-scope projects, with the 80 hours utilized marked as downtimes in both plans. Lastly, the liquid and Copacking lines remain closed during the initial four weeks due to nonexistent demand.

Production and Setup Time

Similarly to the analysis previously conducted for Factory 1, the allocation of time between production activities and setup tasks is a key metric to evaluate. The graph displayed in Figure 38 illustrates the distribution of time devoted to producing finished goods and performing setup activities for the current and optimized plans, considering the entire planning horizon.

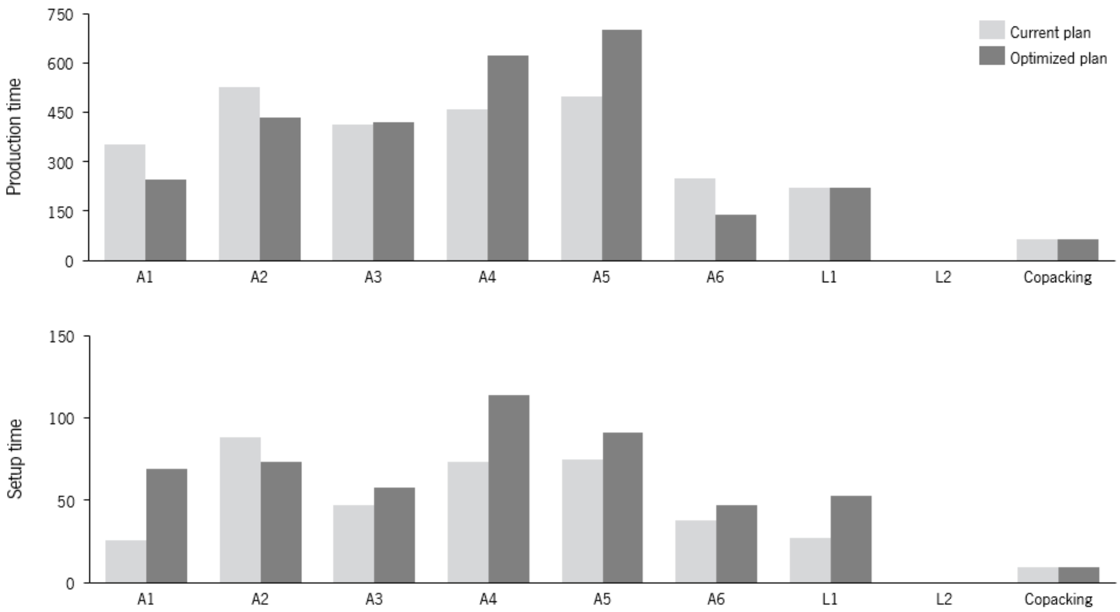

Figure 38: Production and setup time in Factory 2

Regarding the aerosols lines, it is evident that the planning team aims to achieve an equilibrium among them. Thus, balancing the number of workers assigned to the filling lines along the planning weeks. Conversely, the optimization model displayed an inclination towards over-utilizing the A4 and A5 lines. This phenomenon can be attributed to the higher throughput of the aforementioned lines, enabling them to manufacture larger quantities in a shorter timeframe. Corroborating this aspect, is the fact that, as shown in Figure 16, the mentioned two lines are the ones that allocate more variety of products. Furthermore, there is a noticeable increase in setup time across almost all lines, primarily because of the safe quantity implementation. This approach divides certain orders into two productions, leading to additional setup.

5.2. Computational Results

The optimization model formulated in Chapter 4. was implemented in Python using the PuLP library. The instances presented were solved using the solver *Gurobi*, version 10.0.0, on an Intel®vPRO®i7-1265U 1.80GHz processor with 15.4 GB of available RAM, limited to the utilization of 8 threads. To achieve near-optimal solution within a reasonable computational timeframe, four parameters of the *Gurobi* optimization software were carefully configured. These parameters play a central role in controlling inter MILP strategies and optimizing the solving process. These parameters, namely *Heuristics*, *MIPFocus*, *NumericFocus*, and *FeasibilityTol*, were fine-tuned (Gurobi Optimization, nd).

The *Heuristics* parameter regulates the allocation of runtime to feasibility heuristics. Adjusting this parameter can result in an increase in the number and quality of feasible solutions. However, raising the parameter may slow down the rate of progress in achieving the best bound.

The *MIPFocus* parameter provides the ability to adjust the high-level solution strategy and determine the emphasis placed on either feasibility or optimality. When set to 1, the model prioritizes the search for high-quality feasible solutions. On the other hand, if the parameter value is set to 2, the model places greater emphasis on rigorously proving optimality.

The *NumericFocus* parameter determines the level of attention given to detecting and handling numerical problems. By default (setting 0), the code automatically selects a balance between speed and numerical accuracy. However, increasing the parameter to values 1-3 shifts the focus towards prioritizing precise numerical computations. This parameter allows for fine-tuning the numerical robustness of the optimization process based on specific requirements.

The *FeasibilityTol* parameter determines the tolerance level for satisfying constraints in the optimization model. A smaller tolerance value ensures stricter adherence to the constraints, resulting in smaller violations. However, in numerically challenging models, reducing the tolerance may lead to a significant increase in the number of iterations required to reach a solution. The parameter values set for the four specified parameters are provided in Table 12.

Table 12: Gurobi parameters

Heuristics	MIPFocus	NumericFocus	FeasibilityTol
0.4	1	1	0.0001

The instance shown in Table 13 is one of the instances that was tested and refers to the scenario described for Factory 1. The table presents the instance dimensions and the resulting dimensions of the MILP problem. The used data set comprehended 2225 orders for 822 different products, 1829 compatible combinations between items and its production lines, and a time horizon of 17 periods.

Table 13: Problem data and MIP dimensions for Factory 1

Problem Data				MILP Dimensions		
Orders	Products	Combinations	Periods	Constraints	Total variables	Integer variables
2215	822	1829	17	365 785	371 401	315 942

In this scenario, a time restriction of three hours was set for the solution process, but it was found to be insufficient for achieving optimality. The duration of the solution process and the remaining gap are outlined in Table 14. It is noteworthy that although the optimal solution was not achieved, the challenge in narrowing the MILP gap indicates the model's struggle to prove optimality, even though it might be very close to it. Despite not reaching the optimal state within the given time frame, the production plans proposed have proven effective, as demonstrated in the previous section.

Table 14: Solution time and MILP gap for Factory 1

Solution time	MILP gap
10 800 sec	5.43%

The instance previously described, which involved Factory 2, a considerably smaller facility compared to Factory 1, was tested using the same approach. The dataset utilized consisted of a total of 578 orders for 203 distinct products, 296 compatible combinations between items and their respective production lines, with a time span of 17 periods. Table 15 exhibits the problem data and MILP dimensions for the scenario related to Factory 2.

Table 15: Problem data and MILP dimensions for Factory 2

Problem Data				MIP Dimensions		
Orders	Products	Combinations	Periods	Constraints	Total variables	Integer variables
578	203	296	17	92 131	74 989	47 378

In this scenario, a time limit of one hour was imposed for the solving process. However, similar to Factory 1, it was observed that this allocated time was insufficient to achieve an optimal solution. Table 16 illustrates the duration of the solution process and the remaining gap. Although optimality was not attained within the given time frame, the proposed production plans have demonstrated their effectiveness as viable solutions, as it was showcased in the preceding section.

Table 16: Solution time and MILP gap for Factory 2

Solution time	MILP gap
3 600 sec	0.72%

Through the examination and comparison of various instances and by comparing the computational performance of both factories, it was observed that the size of the MILP problem is heavily influenced by the dimension of the problem, determined by the number of orders, different products, compatible combinations, and time periods. This finding indicates a strong correlation between these factors and the computational efficiency of each instance.

6. Conclusion

This concluding chapter provides a critical review and reflection on the work undertaken throughout this thesis. It culminates by highlighting opportunities for future developments and offering suggestions for potential advancements both within the field and in relation to the conducted work.

During the elaboration of this thesis, a comprehensive examination of the subject matter was conducted, leading to valuable insights and contributions to the field. Critical analysis and evaluation of the research findings shed light on the strengths and limitations of the work, emphasizing areas that could be improved and suggesting promising avenues for further exploration.

6.1. Critical Analysis

The objective of this project was to enhance the tactical production planning process of a multinational company operating in the filling industry. The main focus was on developing a comprehensive methodology that could seamlessly integrate into a decision support system, empowering the company's planning department to optimize product and order allocation across multiple filling lines and planning weeks. Additionally, the project aimed to facilitate effective capacity planning and resource allocation in the medium term, ensuring efficient utilization of available resources.

The motivation for undertaking this project stemmed from the recognition that the existing production planning and decision-making processes in the company lacked a solid analytical foundation. It became evident that integrating advanced methodologies and tools was necessary to streamline operations and achieve improved outcomes. By targeting this gap, the project endeavored to furnish the planning department with a robust framework in order to make informed decisions, enhance effectiveness, and improve overall performance in tactical production planning.

Throughout the project, extensive research, analysis, and modeling were conducted to develop an approach customized to the distinct challenges and requirements of the company. The methodology was designed to provide actionable insights, support informed decision-making, and optimize resource and order allocation to drive operational excellence. Collaborating closely with the company's planning department ensured that the developed methodology incorporated their input and feedback, aligning it with their unique requirements and operational context.

Implementing the methodology effectively and integrating it into the decision support system offered the company significant opportunities for improving production planning efficiency. These improvements would not only enhance customer satisfaction by ensuring better order fulfillment but also optimize resource allocation to reduce costs and maximize productivity. Moreover, the project aimed to establish a solid foundation for continuous improvement, enabling the company to adapt and respond effectively to evolving market dynamics and customer demands in the highly competitive filling sector.

The meticulously designed production plans for both Factory 1 and Factory 2 were focused on optimizing efficiency and minimizing costs. The generated plans successfully improved overall productivity, enhanced resource and personnel management, and resulted in cost savings. These advantages were further bolstered by the integration of a decision support system, which brought data-driven analysis and real-time adjustments to enhance reliability and effectiveness in decision-making.

Regarding Factory 1, a 3.4% reduction in unitary cost was achieved due to an increase in the quantity produced. Additionally, multiple filling lines and the overall factory schedule were reduced, primarily because of the implementation of the safe quantity concept. This allowed for the anticipation of more orders and enabled order aggregation to adhere to product constraints. However, there was a need to increase the time dedicated to performing setups in mostly lines. Furthermore, the model improved the management of raw material availability, leading to more orders being produced, albeit with an increase in delays by 9%. Notably, the average delay decreased from 5.33 to 4.61 weeks. A key point about line LA01 is that, being exclusively dedicated to one customer, the optimizer didn't have the expected impact. This was because there was limited flexibility in order allocation regarding the mentioned line.

In Factory 2, there was a significant 10.1% reduction in unitary cost due to a notable increase in production quantity. This reduction was possible as multiple filling lines and the overall factory schedule were streamlined, primarily due to the implementation of the safe quantity concept. This concept had a significant impact on Factory 2, given its overcapacity, allowing for more flexibility in order allocation. Similarly, setup times increased in most filling lines. Additionally, the model enhanced the management of raw material availability, resulting in more orders being fulfilled, even though with an increase in delays by 23%. Importantly, the average delay decreased from 4.57 to 4.08 weeks.

After summarizing the key outcomes for each factory, comparing the results between the factories becomes fundamental. While the optimizer can deliver similar enhancements, the impact observed in Factory 2 is notably more substantial. This difference can be explained by the fact that Factory 2 benefits from additional capacity, offering the model greater flexibility in allocating production orders across different lines during the planning weeks. In conclusion, implementing these production plans elevated operational performance, paving the way for sustainable growth and success for both factories.

Nevertheless, it is of utmost importance to underscore a significant limitation that persisted throughout the course of the conducted work. This limitation primarily stems from the fact that the company operates within a highly restrictive framework, characterized by stringent rules. Consequently, these operational constraints impose substantial limitations on the optimization model employed. To accurately capture and account for the numerous operational constraints inherent in the production context, the optimization model is burdened with a large number of constraints. As a result, the optimization model is compelled to drastically narrow down its solution space, thereby greatly diminishing its potential efficacy and range of feasible solutions. Thus, although the model provides valuable insights, its applicability may be constrained by the specific operational conditions of the examined company.

6.2. Future Research and Development

The execution of the project introduces numerous opportunities for enhancing the decision-making process within the company. In particular, considering the ongoing nature of the current study, it would be beneficial to extend the application of the optimization module to the remaining factories of the international filling company. Given the advantages in terms of costs and efficiency observed in this project, there is an opportunity to leverage these benefits across all the factories.

Furthermore, exploring the potential implementation of a make-to-stock strategy emerges as a promising avenue for further improvement. By adopting this strategy, the company can shift from a make-to-order approach to proactively producing and stocking inventory based on anticipated demand. In this way, this measure can significantly enhance the company's operational efficiency, increase customer satisfaction, and create a competitive advantage in the market.

In the realm of Production Planning, there are areas that hold potential for improvement. These areas span across the three levels, namely operational, tactical, and strategic. At the operational level, optimizing production scheduling and enhancing team management are crucial points. By streamlining the scheduling process, the company can ensure efficient resources utilization and minimize idle time. Effective team management, on the other hand, involves aligning personnel with the production schedule, providing appropriate training and support, and fostering a collaborative environment.

In the strategic domain, the implementation of a zero-based budgeting approach and an integrated pricing strategy emerges as interesting factors. Zero-based budgeting involves thoroughly evaluating and justifying every expense from a clean slate, ensuring that resources are allocated based on priorities and value creation. This approach fosters cost-consciousness, and eliminates inefficiencies. Additionally, integrating pricing strategies into the planning process enables the company to align pricing decisions with production costs, market dynamics, and customer preferences, thereby optimizing profitability.

The scope of future work extends beyond the Production Planning domain. Upon analyzing the findings, a notable observation was the considerable number of delayed orders in both factories. A thorough analysis revealed that the primary cause of these delays was a shortage of raw materials. In light of this discovery, it becomes important to enhance the current work by developing an optimization tool specifically designed to streamline the purchasing and procurement process of raw materials. Such a tool would play a vital role in ensuring the availability of necessary raw materials at the time of production. This development would not only contribute to smoother operations but also lead to improved customer satisfaction and overall performance.

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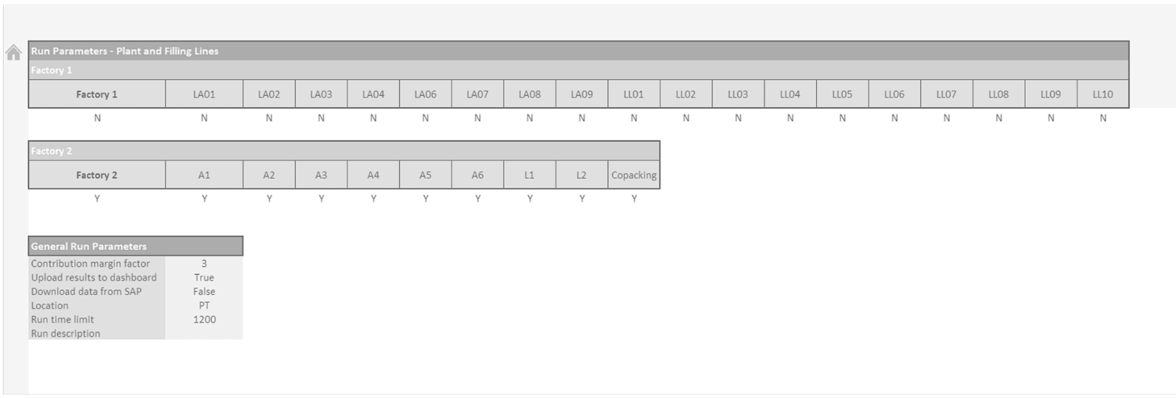
APPENDIX

A INTERFACE PARAMETERIZATION SHEETS

The interface is partitioned into three primary sections, with one of these sections being further divided into two distinct parts, each dedicated to a specific factory. Subsequently, a comprehensive depiction of the principal features of each section and the data available for parameterization unfollows. It is important to note that some values are hidden due to the data confidentiality required by the company.

The sheet related to general settings includes all the parameters needed for executing the optimization module. These parameters encompass the production facilities and filling lines for which the model will formulate the plan. Additionally, technical factors like optimization run time, and the need to retrieve data from SAP, are incorporated. A visual representation of this document is presented in Figure 39.



Run Parameters - Plant and Filling Lines

Factory 1

Factory 1	LA01	LA02	LA03	LA04	LA06	LA07	LA08	LA09	LL01	LL02	LL03	LL04	LL05	LL06	LL07	LL08	LL09	LL10
N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N

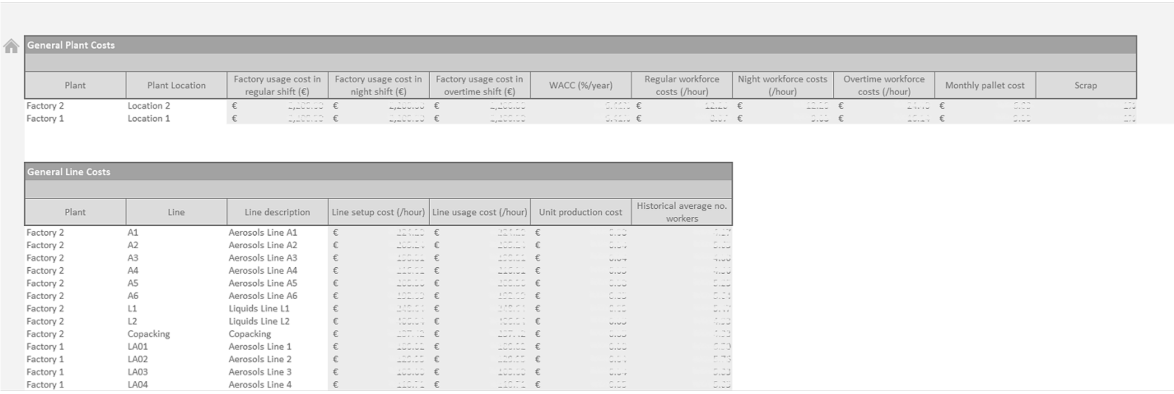
Factory 2

Factory 2	A1	A2	A3	A4	A5	A6	L1	L2	Copacking
Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

General Run Parameters	
Contribution margin factor	3
Upload results to dashboard	True
Download data from SAP	False
Location	PT
Run time limit	1200
Run description	

Figure 39: General settings sheet

The spreadsheet concerning overall costs provides a comprehensive breakdown of costs for both the manufacturing factory and the associated filling lines. Regarding the manufacturing factory costs, it encompasses expenses for regular, night, and overtime operations, along with factors like scrap percentage and the WACC value, among others. Concerning the parameters for filling lines, it incorporates production costs, setup expenses for each filling line, and the average workforce count per line. The specifics of these parameters are illustrated in Figure 40.



General Plant Costs

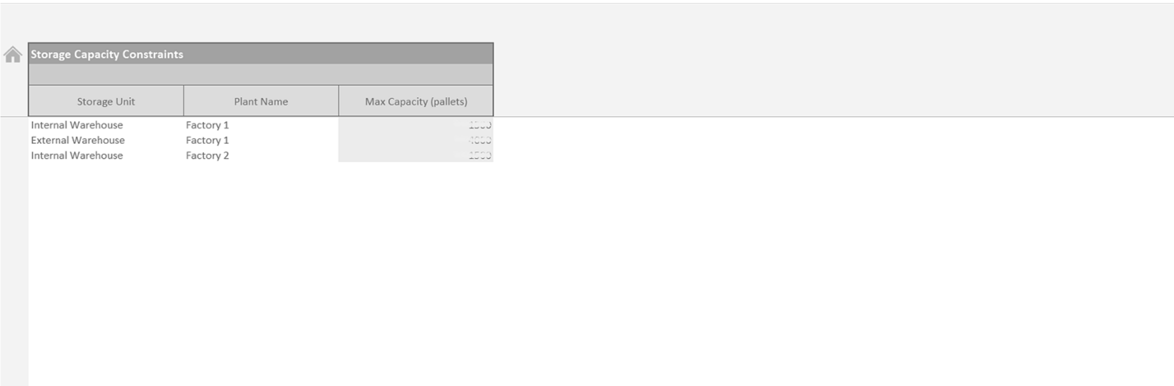
Plant	Plant Location	Factory usage cost in regular shift (€)	Factory usage cost in night shift (€)	Factory usage cost in overtime shift (€)	WACC (%/year)	Regular workforce costs (/hour)	Night workforce costs (/hour)	Overtime workforce costs (/hour)	Monthly pallet cost	Scrap
Factory 2	Location 2	€ [illegible]	€ [illegible]	€ [illegible]	[illegible]	€ [illegible]	€ [illegible]	€ [illegible]	€ [illegible]	[illegible]
Factory 1	Location 1	€ [illegible]	€ [illegible]	€ [illegible]	[illegible]	€ [illegible]	€ [illegible]	€ [illegible]	€ [illegible]	[illegible]

General Line Costs

Plant	Line	Line description	Line setup cost (/hour)	Line usage cost (/hour)	Unit production cost	Historical average no. workers
Factory 2	A1	Aerosols Line A1	€ [illegible]	€ [illegible]	€ [illegible]	[illegible]
Factory 2	A2	Aerosols Line A2	€ [illegible]	€ [illegible]	€ [illegible]	[illegible]
Factory 2	A3	Aerosols Line A3	€ [illegible]	€ [illegible]	€ [illegible]	[illegible]
Factory 2	A4	Aerosols Line A4	€ [illegible]	€ [illegible]	€ [illegible]	[illegible]
Factory 2	A5	Aerosols Line A5	€ [illegible]	€ [illegible]	€ [illegible]	[illegible]
Factory 2	A6	Aerosols Line A6	€ [illegible]	€ [illegible]	€ [illegible]	[illegible]
Factory 2	L1	Liquids Line L1	€ [illegible]	€ [illegible]	€ [illegible]	[illegible]
Factory 2	L2	Liquids Line L2	€ [illegible]	€ [illegible]	€ [illegible]	[illegible]
Factory 2	Copacking	Copacking	€ [illegible]	€ [illegible]	€ [illegible]	[illegible]
Factory 1	LA01	Aerosols Line 1	€ [illegible]	€ [illegible]	€ [illegible]	[illegible]
Factory 1	LA02	Aerosols Line 2	€ [illegible]	€ [illegible]	€ [illegible]	[illegible]
Factory 1	LA03	Aerosols Line 3	€ [illegible]	€ [illegible]	€ [illegible]	[illegible]
Factory 1	LA04	Aerosols Line 4	€ [illegible]	€ [illegible]	€ [illegible]	[illegible]

Figure 40: General costs sheet

This sheet allows to set-up the maximum capacity, in pallets, available in each warehouse of the different factories. Figure 41 contains the mentioned sheet.

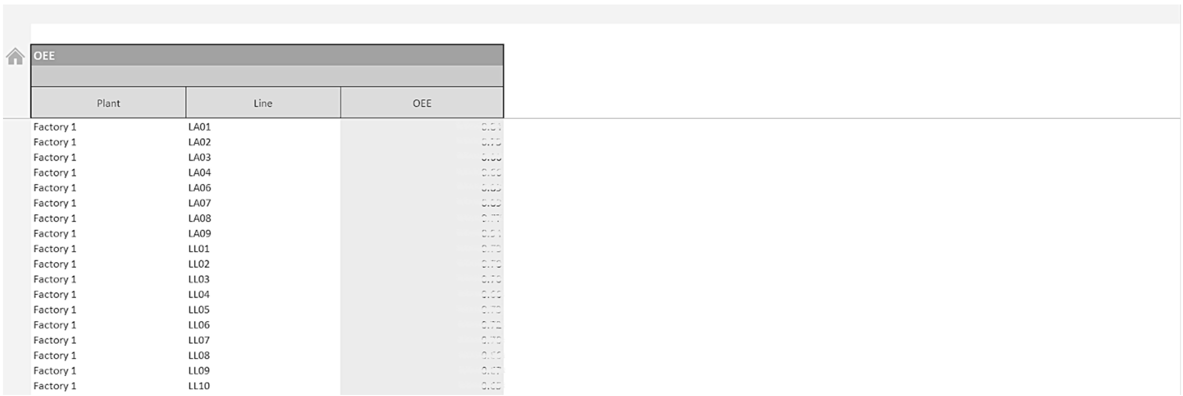


Storage Capacity Constraints

Storage Unit	Plant Name	Max Capacity (pallets)
Internal Warehouse	Factory 1	[illegible]
External Warehouse	Factory 1	[illegible]
Internal Warehouse	Factory 2	[illegible]

Figure 41: Storage constraints sheet

The OEE spreadsheet contains the OEE values disregarding the setups for each filling line of both plants, and it is represented in Figure 42.



OEE

Plant	Line	OEE
Factory 1	LA01	[illegible]
Factory 1	LA02	[illegible]
Factory 1	LA03	[illegible]
Factory 1	LA04	[illegible]
Factory 1	LA06	[illegible]
Factory 1	LA07	[illegible]
Factory 1	LA08	[illegible]
Factory 1	LA09	[illegible]
Factory 1	LL01	[illegible]
Factory 1	LL02	[illegible]
Factory 1	LL03	[illegible]
Factory 1	LL04	[illegible]
Factory 1	LL05	[illegible]
Factory 1	LL06	[illegible]
Factory 1	LL07	[illegible]
Factory 1	LL08	[illegible]
Factory 1	LL09	[illegible]
Factory 1	LL10	[illegible]

Figure 42: OEE sheet

The Global Working Schedule sheet allows the parameterization of various aspects regarding the current working schedule for both factories. It also enables to establish the different potential working schedules for each factory. Additionally, this spreadsheet covers the hours and shifts worked, in regular, night, and overtime, for each of these schedules. Figure 43 represents a screenshot of the Global Working Schedule sheet.

Initial Working Schedule

Plant	Current Working Schedule	Next changeable week
Factory 2	24/5	3
Factory 1	24/7	3

Available Working Schedule

Plant	Working Schedule	Regular hours available / week	Night hours available / week	Extra hours available / week	Factory opened regular shifts	Factory opened night shifts	Factory opened extra shifts
Factory 2	0/0	0	0	0	0	0	0
Factory 2	8/1	8	0	0	1	0	0
Factory 2	8/2	16	0	0	2	0	0
Factory 2	8/3	24	0	0	3	0	0
Factory 2	8/4	32	0	0	4	0	0
Factory 2	8/5	40	0	0	5	0	0
Factory 2	16/3	48	0	0	6	0	0
Factory 2	16/4 - 1 shift	56	0	0	7	0	0
Factory 2	16/4	64	0	0	8	0	0
Factory 2	16/5 - 1 shift	72	0	0	9	0	0
Factory 2	16/5	80	0	0	10	0	0
Factory 2	17/5	80	0	5	10	0	0.625
Factory 2	18/5	80	0	10	10	0	1.25
Factory 2	19.5/5	80	0	18	10	0	2.25
Factory 2	24/5	80	40	0	10	5	0
Factory 1	0/0	0	0	0	0	0	0
Factory 1	8/5	40	0	0	5	0	0
Factory 1	8/5 + 2 shifts	56	0	0	7	0	0
Factory 1	16/5	80	0	0	10	0	0
Factory 1	24/5	80	40	0	10	5	0
Factory 1	24/5 + 1 shift	80	40	8	10	5	1
Factory 1	24/5 + 2 shifts	80	40	16	10	5	2

Figure 43: Global working schedule sheet

The sheet related to Line Schedule, presented in Figure 44, permits users to select the working schedules for each filling line for the present week and the following four planning weeks.

Line Schedule

	Week 31	Week 32	Week 33	Week 34	Week 35
Line	Week 0	Week 1	Week 2	Week 3	Week 4
LA01	8/5	8/5	8/5	8/5	8/5
LA02	24/5 + 2 shifts	24/5 + 2 shifts	24/5 + 2 shifts	24/5 + 2 shifts	24/5 + 2 shifts
LA03	24/5 + 2 shifts	24/5 + 2 shifts	24/5 + 2 shifts	24/5 + 2 shifts	24/5 + 2 shifts
LA04	24/5 + 2 shifts	24/5 + 2 shifts	24/5 + 2 shifts	24/5 + 2 shifts	24/5 + 2 shifts
LA06	8/5	16/5	16/5	8/5	8/5
LA07	24/5	24/5	24/5	24/5	24/5
LA08	24/5	24/5	24/5	24/5	24/5
LA09	24/5	24/5	24/5	24/5	24/5
LL01	0/0	16/5	16/5	16/5	16/5
LL02	0/0	0/0	0/0	0/0	0/0
LL04	8/5	8/5	8/5	8/5	8/5
LL05	0/0	0/0	0/0	0/0	0/0
LL06	24/5	24/5	24/5	24/5	24/5
LL08	16/5	16/5	16/5	16/5	16/5
LL09	8/5	0/0	0/0	0/0	0/0
LL10	8/5 + 2 shifts	8/5	8/5	16/5	16/5

Figure 44: Line schedule sheet

The sheet regarding Line Closure depicted in Figure 45 contains a table depicting the working schedules that cannot be chosen for each filling line during the 17 weeks of planning.

Line Closure

Working Schedules

Filling Line	Week	0/0	8/5	8/5 + 2 shifts	16/5	24/5	24/5 + 1 shift	24/5 + 2 shifts	24/7
LA01	32			X	X	X	X	X	X
LA02	32								X
LA03	32								X
LA04	32								X
LA06	32								X
LA07	32								X
LA08	32								X
LA09	32								X
LL01	32					X	X	X	X
LL02	32		X	X	X	X	X	X	X
LL04	32					X	X	X	X
LL05	32								
LL06	32						X	X	X
LL08	32					X	X	X	X
LL09	32			X	X	X	X	X	X
LL10	32					X	X	X	X
LA01	33			X	X	X	X	X	X
LA02	33								X

Figure 45: Line closure sheet

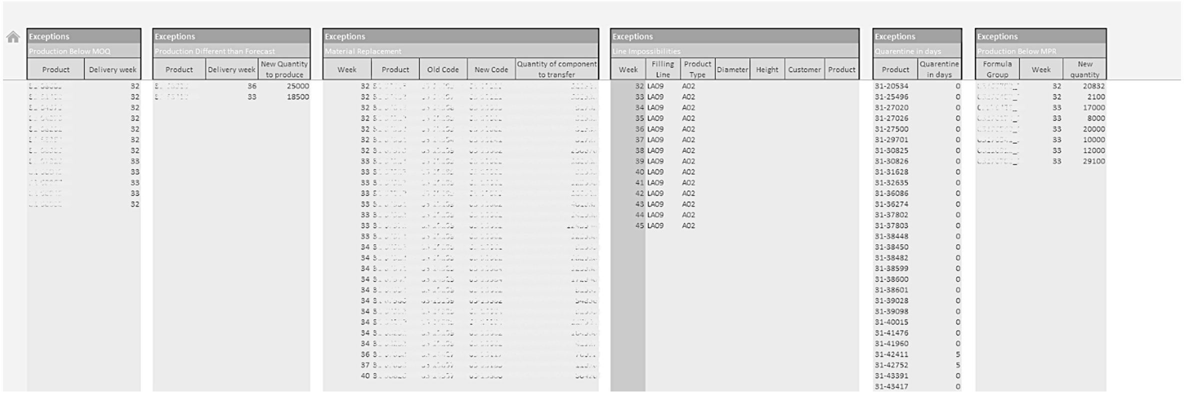
The Line Downtime spreadsheet allows for the specification of planned downtimes during regular, night and overtime periods, for each filling line in every week of the planning horizon. The mentioned sheet is illustrated in Figure 46.

Line Downtime

Line	Week	Planned downtime - regular hours (h)	Planned downtime - night hours (h)	Planned downtime - extra hours (h)
LA01	32	0	0	0
LA02	32	0	0	0
LA03	32	0	0	0
LA04	32	0	0	0
LA06	32	0	0	0
LA07	32	0	0	0
LA08	32	0	0	0
LA09	32	0	0	0
LL01	32	0	0	0
LL02	32	0	0	0
LL04	32	0	0	0
LL05	32	0	0	0
LL06	32	0	0	0
LL08	32	0	0	0
LL09	32	0	0	0
LL10	32	0	0	0
LA01	33	16	0	0
LA02	33	32	16	8

Figure 46: Line downtime sheet

The Exceptions sheet, represented in Figure 47 is responsible for including various exceptions such as production below MOQ, production different from forecast, material replacement, line impossibilities, quarantine time, and production below MPR. The explanation of all these exceptions is provided in Table 5, which is present in Section 4.4..



Exceptions	
Production Below MOQ	
Product	Delivery week
[illegible]	32
[illegible]	32
[illegible]	32
[illegible]	32
[illegible]	32
[illegible]	32
[illegible]	32
[illegible]	33
[illegible]	33
[illegible]	33
[illegible]	33
[illegible]	32

Exceptions		
Production Different than Forecast		
Product	Delivery week	New Quantity to produce
[illegible]	36	25000
[illegible]	33	18500

Exceptions				
Material Replacement				
Week	Product	Old Code	New Code	Quantity of component to transfer
32	[illegible]	[illegible]	[illegible]	[illegible]
32	[illegible]	[illegible]	[illegible]	[illegible]
32	[illegible]	[illegible]	[illegible]	[illegible]
32	[illegible]	[illegible]	[illegible]	[illegible]
32	[illegible]	[illegible]	[illegible]	[illegible]
32	[illegible]	[illegible]	[illegible]	[illegible]
32	[illegible]	[illegible]	[illegible]	[illegible]
33	[illegible]	[illegible]	[illegible]	[illegible]
33	[illegible]	[illegible]	[illegible]	[illegible]
33	[illegible]	[illegible]	[illegible]	[illegible]
33	[illegible]	[illegible]	[illegible]	[illegible]
33	[illegible]	[illegible]	[illegible]	[illegible]
33	[illegible]	[illegible]	[illegible]	[illegible]
33	[illegible]	[illegible]	[illegible]	[illegible]
33	[illegible]	[illegible]	[illegible]	[illegible]
34	[illegible]	[illegible]	[illegible]	[illegible]
34	[illegible]	[illegible]	[illegible]	[illegible]
34	[illegible]	[illegible]	[illegible]	[illegible]
34	[illegible]	[illegible]	[illegible]	[illegible]
34	[illegible]	[illegible]	[illegible]	[illegible]
34	[illegible]	[illegible]	[illegible]	[illegible]
34	[illegible]	[illegible]	[illegible]	[illegible]
34	[illegible]	[illegible]	[illegible]	[illegible]
34	[illegible]	[illegible]	[illegible]	[illegible]
34	[illegible]	[illegible]	[illegible]	[illegible]
36	[illegible]	[illegible]	[illegible]	[illegible]
37	[illegible]	[illegible]	[illegible]	[illegible]
40	[illegible]	[illegible]	[illegible]	[illegible]

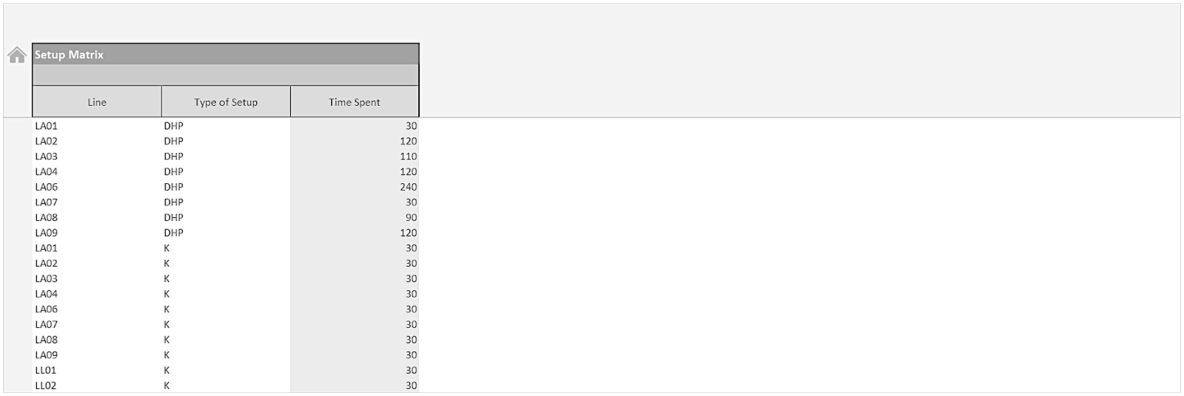
Exceptions						
Line Impossibilities						
Week	Filling Line	Product Type	Diameter	Height	Customer	Product
32	LA09	A02				
33	LA09	A02				
34	LA09	A02				
35	LA09	A02				
36	LA09	A02				
37	LA09	A02				
38	LA09	A02				
39	LA09	A02				
40	LA09	A02				
41	LA09	A02				
42	LA09	A02				
43	LA09	A02				
44	LA09	A02				
45	LA09	A02				

Exceptions	
Quarentine in days	
Product	Quarentine in days
31-20534	0
31-25496	0
31-27020	0
31-27026	0
31-27500	0
31-29701	0
31-30825	0
31-30826	0
31-31628	0
31-32635	0
31-36086	0
31-36274	0
31-37802	0
31-37803	0
31-38448	0
31-38450	0
31-38482	0
31-38599	0
31-38600	0
31-38601	0
31-39028	0
31-39098	0
31-40015	0
31-41476	0
31-41960	0
31-42411	5
31-42752	5
31-43391	0
31-43417	0

Exceptions		
Production Below MPR		
Formula Group	Week	New quantity
[illegible]	32	20832
[illegible]	32	2100
[illegible]	33	17000
[illegible]	33	8000
[illegible]	33	20000
[illegible]	33	10000
[illegible]	33	12000
[illegible]	33	29100

Figure 47: Exceptions sheet

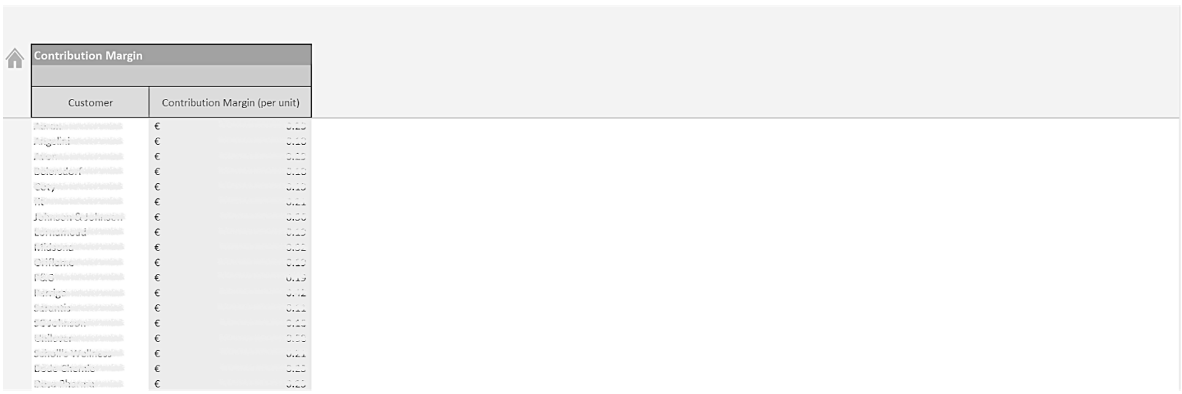
The spreadsheet presented in Figure 48, related to the Setup Time Matrix, includes a table with all possible setup types for each filling line and their respective associated times.



Setup Matrix		
Line	Type of Setup	Time Spent
LA01	DHP	30
LA02	DHP	120
LA03	DHP	110
LA04	DHP	120
LA06	DHP	240
LA07	DHP	30
LA08	DHP	90
LA09	DHP	120
LA01	K	30
LA02	K	30
LA03	K	30
LA04	K	30
LA06	K	30
LA07	K	30
LA08	K	30
LA09	K	30
LL01	K	30
LL02	K	30

Figure 48: Setup time matrix sheet

The Contribution Margin spreadsheet includes the contribution margins per unit categorized by the customers of each factory. The contribution margin represents the cost per unit to cancel an order from a specific customer. Figure 49 contains a visual representation of this sheet.



Contribution Margin	
Customer	Contribution Margin (per unit)
[illegible]	€ [illegible]
[illegible]	€ [illegible]
[illegible]	€ [illegible]
[illegible]	€ [illegible]
[illegible]	€ [illegible]
[illegible]	€ [illegible]
[illegible]	€ [illegible]
[illegible]	€ [illegible]
[illegible]	€ [illegible]
[illegible]	€ [illegible]
[illegible]	€ [illegible]
[illegible]	€ [illegible]
[illegible]	€ [illegible]
[illegible]	€ [illegible]
[illegible]	€ [illegible]
[illegible]	€ [illegible]
[illegible]	€ [illegible]
[illegible]	€ [illegible]

Figure 49: Contribution margin sheet

The sheet Client Agreements, presented in Figure 50, specifies the fixed and binding periods for each technology of each customer.

Client Agreements Data

Plant	Customer	Customer Group	Planning Frequency	Fixed Period	Fixed Period (weeks)	Material binding period	Binding period (weeks)	Technology
Factory 1	[illegible]	[illegible]	Weekly	Current week + 4 weeks	4	Fix Period + 4 months	16	Aerosols
Factory 1	[illegible]	[illegible]	Weekly	Current week + 3 weeks	3	Fix Period + 4 months	16	Liquids
Factory 1	[illegible]	[illegible]	Weekly	Current week + 3 weeks	3	Fix Period +Â 8 weeks	8	Aerosols
Factory 1	[illegible]	[illegible]	Weekly	Current week + 6 weeks	6	Fix Period + 5 weeks	5	Aerosols
Factory 1	[illegible]	[illegible]	Weekly	Fix Period = Longest Material LT + 2 weeks	10		5	Liquids
Factory 1	[illegible]	[illegible]	Monthly	Current month + 3 months (AL items - Luxury portfolio)	12	12 wks	12	Aerosols
Factory 1	[illegible]	[illegible]	Monthly	Current month + 2 months	8	equal to fix period	0	Aerosols
Factory 1	[illegible]	[illegible]	Weekly	Current week + 4 weeks	4	Fix Period + 3 months	12	Aerosols
Factory 1	[illegible]	[illegible]	Monthly	Current month + 2 months	8	Fix Period + 3 months	12	Liquids
Factory 1	[illegible]	[illegible]	Monthly	Current month + 2 months	8	Fix Period + 3 months	12	Aerosols
Factory 1	[illegible]	[illegible]	Weekly	1+5 weeks	6	Fix Period + 7 weeks	7	Aerosols
Factory 1	[illegible]	[illegible]	Weekly	1+5 weeks	6	Fix Period + 7 weeks	7	Liquids
Factory 1	[illegible]	[illegible]	Weekly	Current month + 6/10 weeks FG depending	10	Fix Period + 12 weeks	12	Aerosols
Factory 1	[illegible]	[illegible]	Monthly	Spot orders	0	-	0	Aerosols
Factory 1	[illegible]	[illegible]	Monthly	Current month + 2 months	8	Fix Period + 2 months	8	Liquids
Factory 1	[illegible]	[illegible]	Monthly	Current month + 2 months	8	Fix Period + 3 months	12	Aerosols
Factory 1	[illegible]	[illegible]	Monthly	Current month + 3 months	8	Fix Period + 3 months	12	Aerosols
Factory 1	[illegible]	[illegible]	Monthly	Current month + 2 months	8	Fix Period + 1 month	4	Aerosols
Factory 1	[illegible]	[illegible]	Daily	Spot Orders	0		0	Liquids
Factory 1	[illegible]	[illegible]	Monthly	Current month + 3 months	12	Fix Period + 3 months	12	Aerosols
Factory 1	[illegible]	[illegible]	Weekly	36 hours	0		0	Aerosols
Factory 1	[illegible]	[illegible]	Weekly	n+1 week	1	Fix period + 4 weeks	4	Liquids

Figure 50: Client agreements sheet

The Plan Changes sheet includes the changes (additions, deletions, or replacements) desired by the planning team to be manually integrated into the final output production plan. Figure 51 depicts the mentioned sheet.

Plan Changes

Add or delete production

Change	Product	Date	Quantity	Filling Line

Plan Changes

Replace production

Product	Past Week	Past Filling Line	Past Quantity	Week	Filling Line	Quantity

Figure 51: Plan changes sheet

The sheet named Production Plan, illustrated in Figure 52, comprises the ultimate production plan, illustrating the weeks, filling lines, and quantities for each product's manufacturing. This information will later be integrated into the company's SAP system and put to use by the team.

Figure 52: Production plan sheet

B Dashboard views

The developed dashboard comprises a total of nine distinct views, each with a unique focus: Overview, Detailed, Capacity, Production, Orders, Costs, Setups, Raw Materials, Comparison. This appendix includes screenshots of all the mentioned views, offering select examples of visuals within each view. It is important to note that the examples provided are not exhaustive explained but rather offer illustrative instances of the diverse visuals available to the planning team. Furthermore, in adherence to the company's confidentiality requirements, the views are not fully displayed, with certain values intentionally hidden.

Firstly, the Overview view offers a comprehensive and not exhaustive analysis of the plan, presenting charts that enable the planning team to access general insights into the optimized plan and important KPIs concerning both filling lines and the factory as a whole. This view provides details about the total orders, encompassing anticipated, delayed, and cancelled orders, plan-related costs, and factory capacity. Furthermore, it showcases graphs illustrating the total quantities ordered and produced for each customer, working schedules of the factory and each filling line, filling lines' hours and shifts contracted, critical components during the planning weeks, and more. Additionally, it holds details regarding the necessary workers for each filling line in every week. It is worth mentioning that the visuals can be filtered based on the plan ID, plant, planning weeks, product type, and filling line. A segment of the Power BI Overview view is depicted in Figure 53.

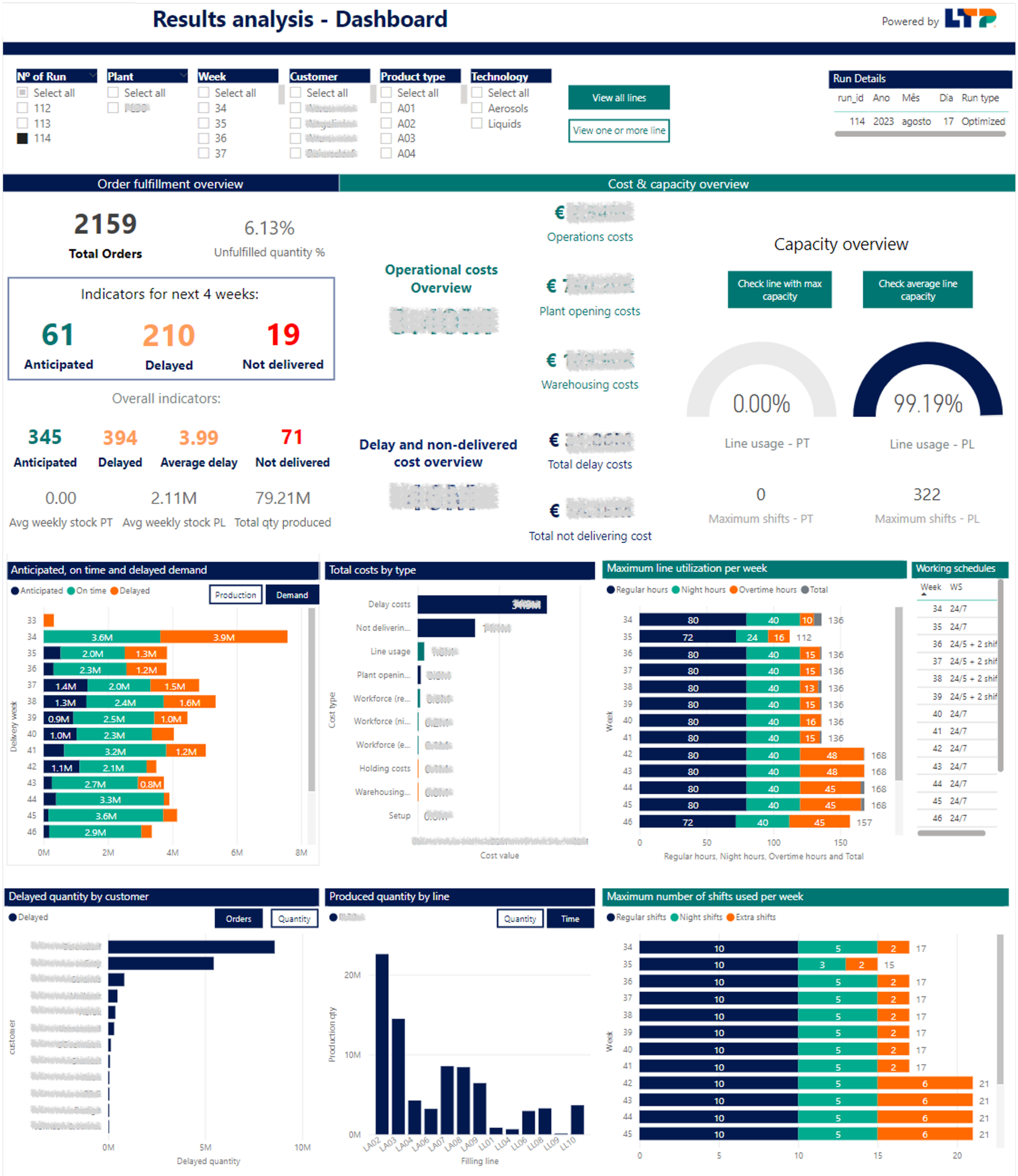


Figure 53: Overview view

The Detail View serves as a comprehensive tool for conducting in-depth analysis and continuous monitoring of the optimized plan. This view encompassed insights into the orders status by week, specifically canceled orders, along with the corresponding reasons for their cancellation. Additionally, the Detailed view presents data regarding the MPR and the specific products that fall under each family category. The focal point of this view is a table that consolidates various facets of the production plan. This table includes several details such as the product, the designated delivery week, and specific characteristics encompassing descriptions, product types, diameters, and heights. Furthermore, the table contains the quantity that has been produced, alongside the corresponding filling line and the week of production. Moreover, the Detailed view goes above and beyond by providing intricate insights into the components of individual products. This includes detailed information such as component codes and descriptions, necessities for each production, and the existing stock levels at the culmination of each week. Additionally, this view extends its reach to encompass the raw materials requirements necessary for other productions. This view is represented in Figure 54.

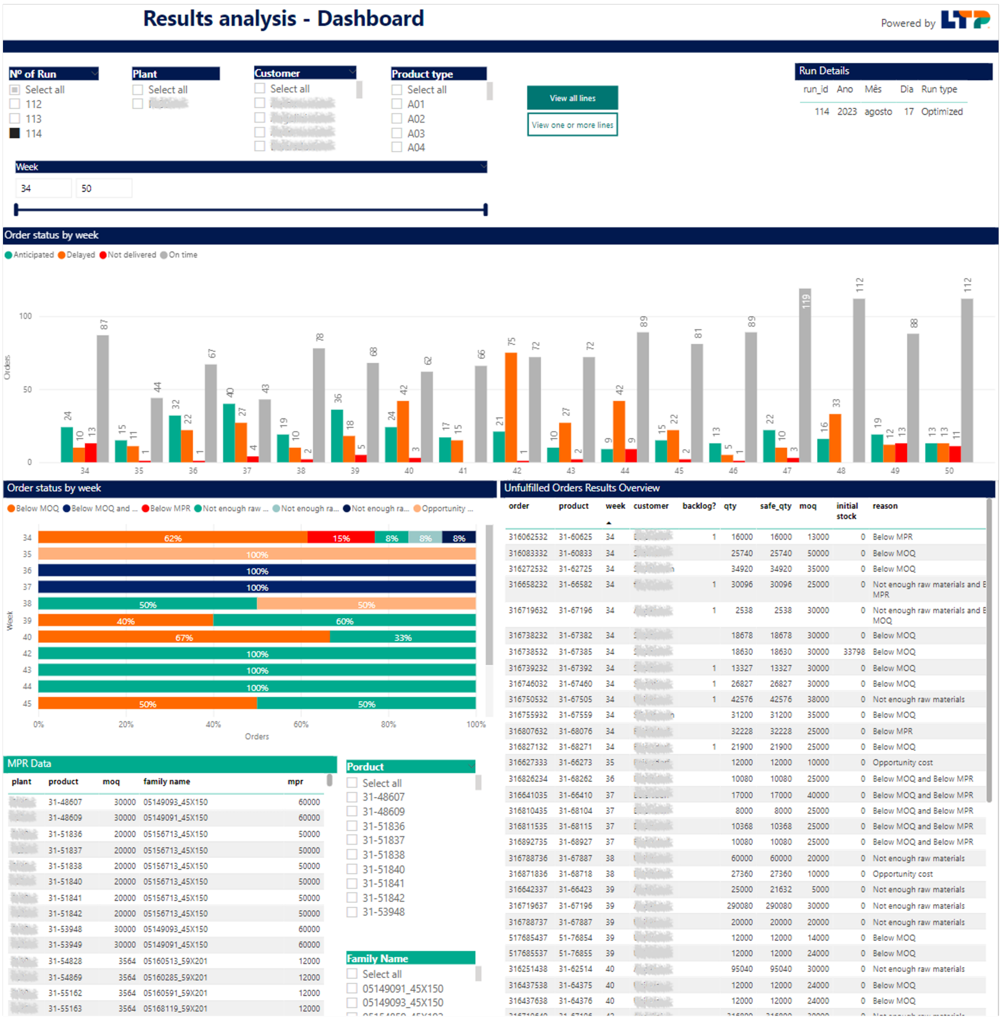


Figure 54: Detail view

The Capacity view encompasses a range of visual elements designed to assess and oversee the overall factory capacity, including capacity in regular, night and overtime. It also presents individual capacities of each filling line, during the diverse planning weeks. Moreover depicts the time spent on actual production or setups for each filling line and week. This view provides a comprehensive understanding of the factory's production capacities, enabling effective monitoring of its capacity utilization. It's a valuable tool for evaluating the capacity of the factory and gaining insights into filling lines' usage. The Capacity view is illustrated in Figure 55.

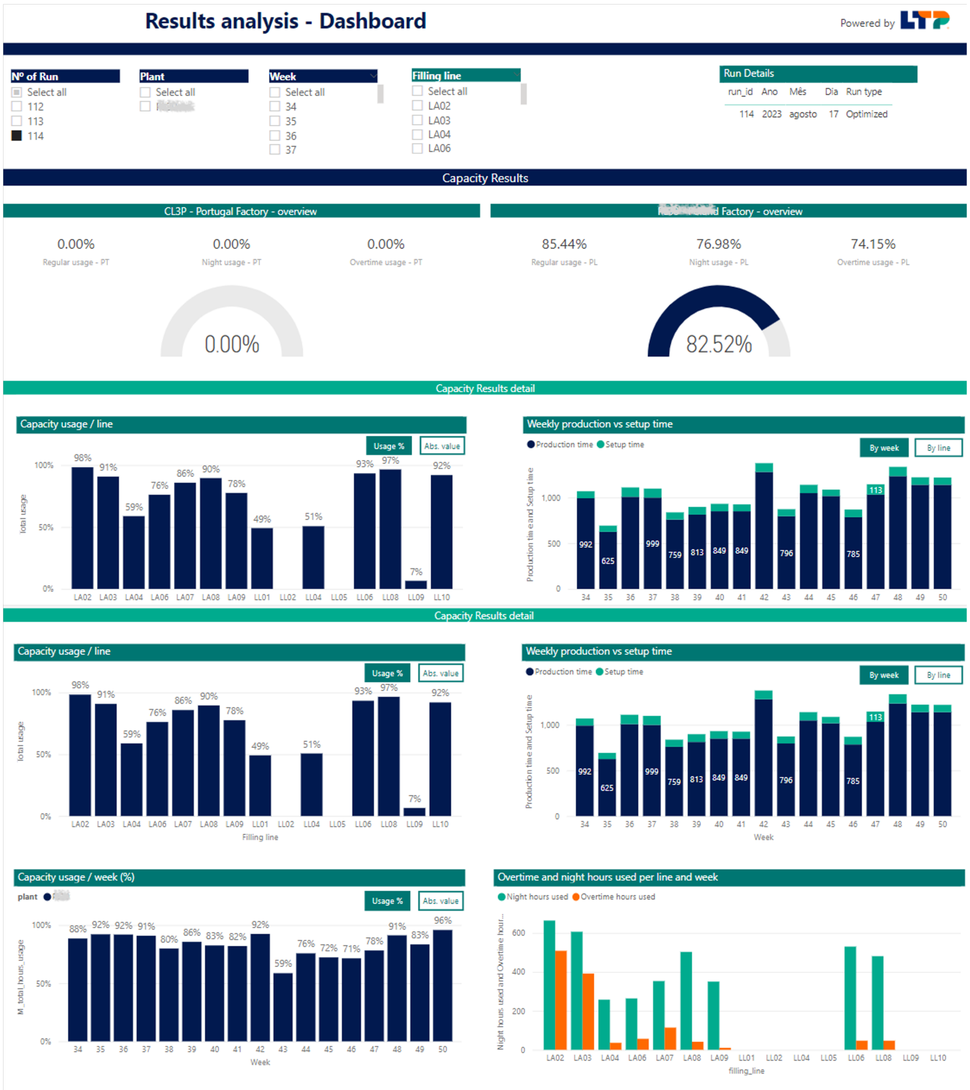


Figure 55: Capacity view

The Production view provides a visual representation of production-related data through various graphs. In a concise format, it shows some production indicators - unfulfilled quantity and total quantity produced. Furthermore, indicated the total time allocated for producing quantities on each filling line, and the quantity demanded and produced during different planning weeks. The Production view is also responsible for tracking the data related to the warehouses by presenting the progression of stock levels. Towards the bottom of the view, there's a summarized table that presents product details, descriptions, associated filling lines, quantities, throughput, and production time. The view offers insight into which filling lines each product can be produced on, along with the corresponding throughputs and production times. This facilitates a comparison of line performance, aiding the planning team in comprehending the optimization model's decisions. A screenshot of the Production view is presented in Figure 56.

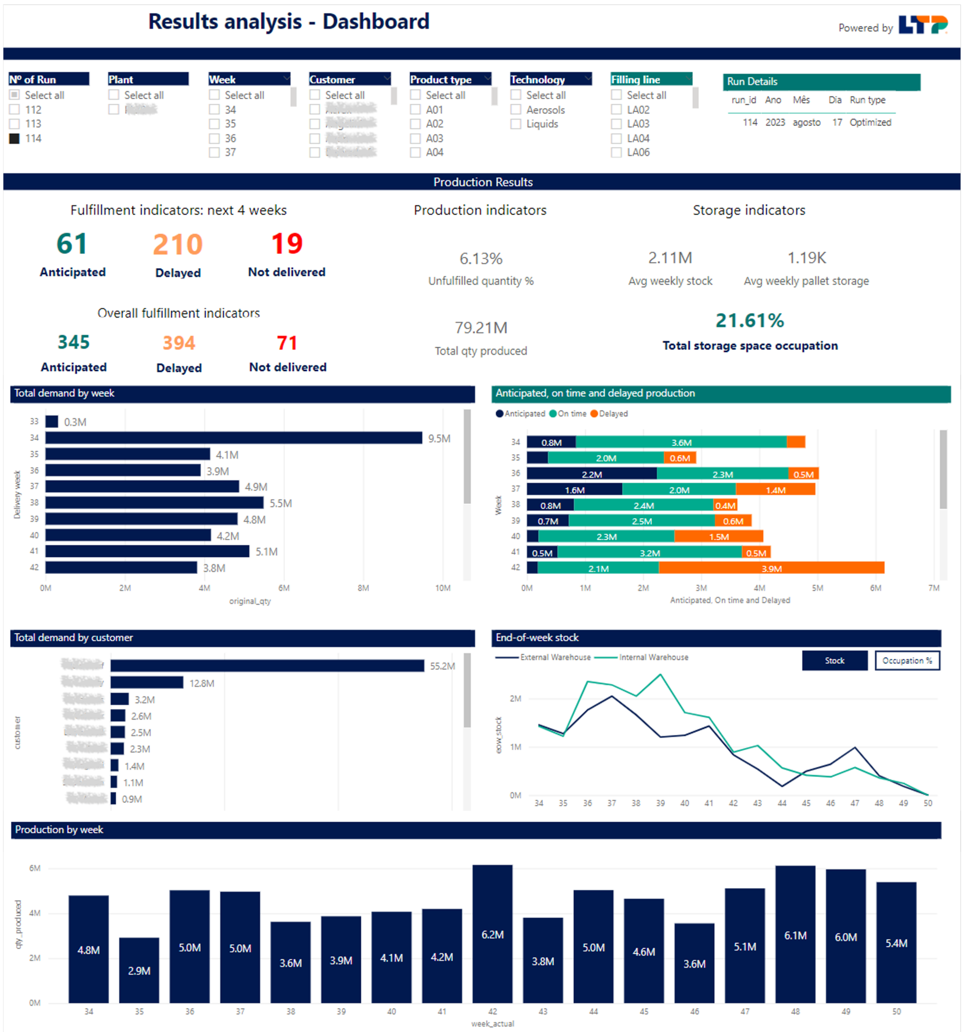


Figure 56: Production view

The Orders view provides comprehensive insights into the status of orders, offering detailed information on anticipated and delayed production quantities, along with the associated anticipation and delay periods in weeks. Graphs illustrating customer-specific trends in anticipation, delay, and cancellation are also presented. Furthermore, this view encompasses data related to the safe quantity, both categorized by customer and by week. Notably, the view concludes with a table that outlines the costs associated with order cancellations and delays. This table is intended to facilitate a deeper understanding of the decision-making process guided by the optimization model. The visual representation of this view is showcased in Figure 57.

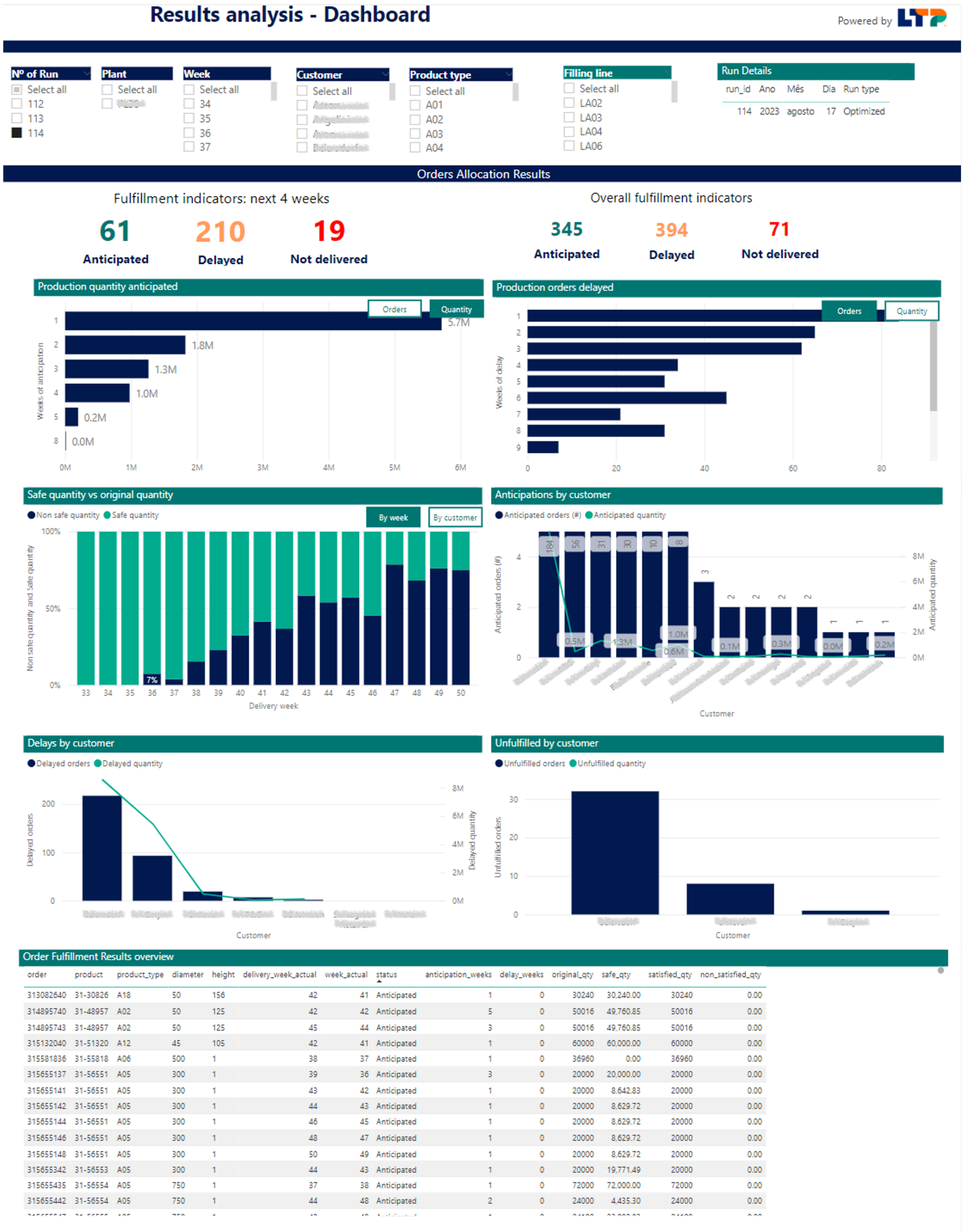


Figure 57: Orders view

Within the Costs view, is presented a breakdown of expenses linked to the optimized production plan, categorized across various segments: warehousing, inventory holding, filling line utilization, workforce, delays, non-deliveries, and factory opening. This thorough categorization provides a detailed insight into the financial aspects of the optimized plan, allowing their evaluation and improvement. Furthermore, the Costs view segregates these expenses based on the planning timeline and across different filling lines. This meticulous separation facilitates comprehensive monitoring and robust examination of the monetary implications embedded within the production plan. Figure 58 showcases the Costs view along with its accompanying graphs.

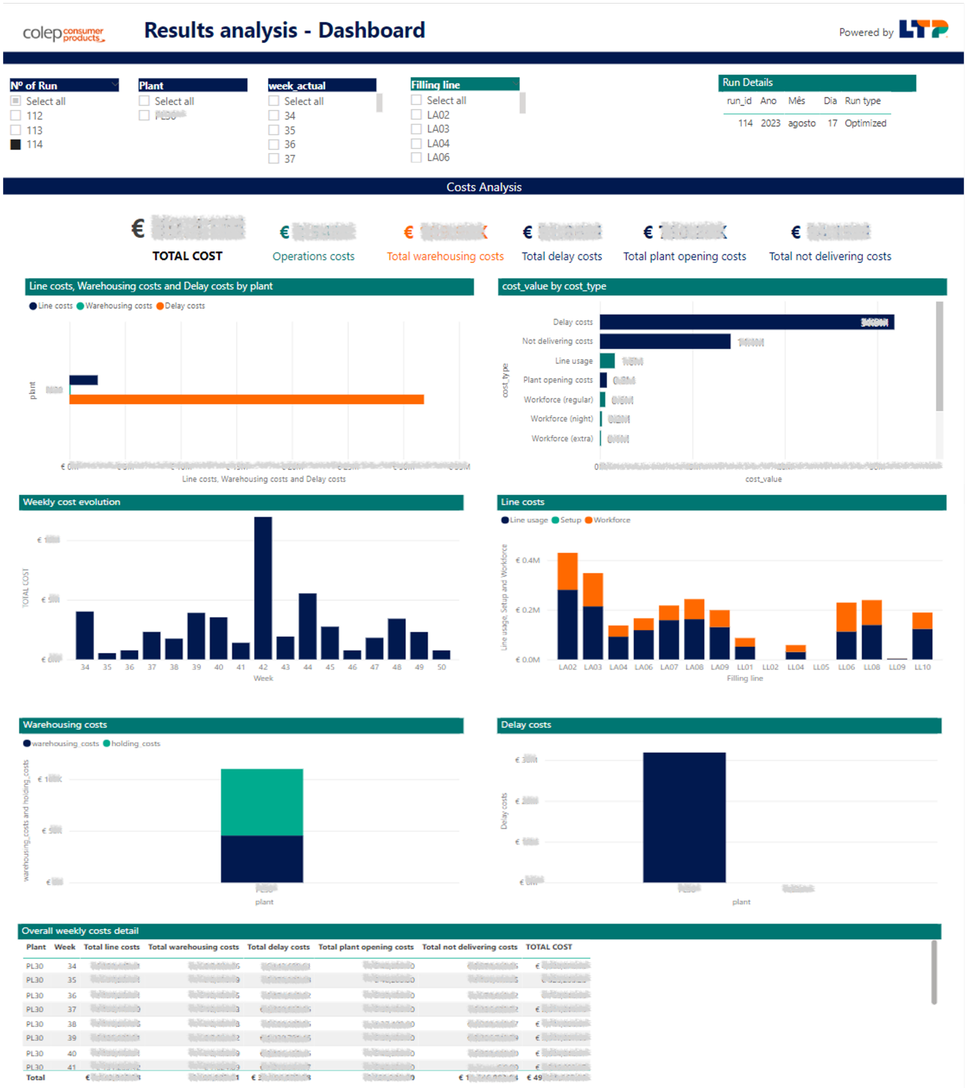


Figure 58: Costs view

The Setups view provides a comprehensive overview of setup-related data, including the overall count of setups and the cumulative time expended on setups across the 17 planning weeks. Additionally, it offers insights into the distribution of setups categorized by type and classified by plant, filling line, and the respective planning week. This view delves further into a detailed breakdown of the distinct setups employed within each filling line and week, detailing the setup count and individual setup duration. The visual representation of this comprehensive view can be observed in Figure 59.

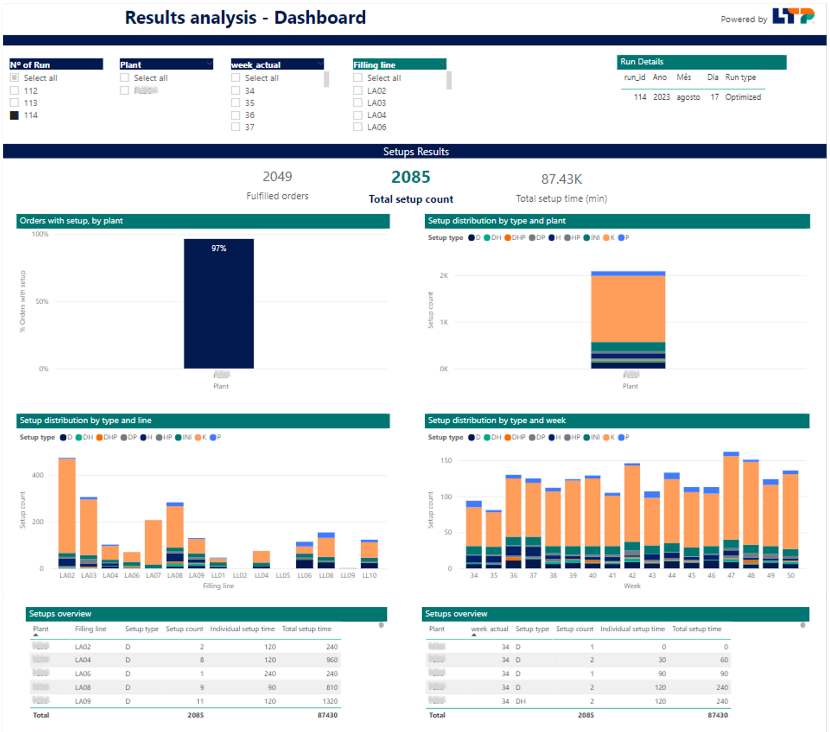


Figure 59: Setups view

The Raw Materials view encompasses a comprehensive collection of data pertaining to raw materials, categorized into two primary groups: chemicals and components/materials. Within this view, each group features information regarding weekly raw material consumption, end-of-week inventory levels, and both predicted and model-suggested arrival quantities. A summarizing table at the view's conclusion provides a holistic overview of raw material details. This table includes data for each planning week, such as raw material code, description, unit of measurement, and classification. Additionally, it covers initial stock, consumption, projected and suggested arrivals, and end-of-week inventory levels. The visual representation of this comprehensive view is available in Figure 60.

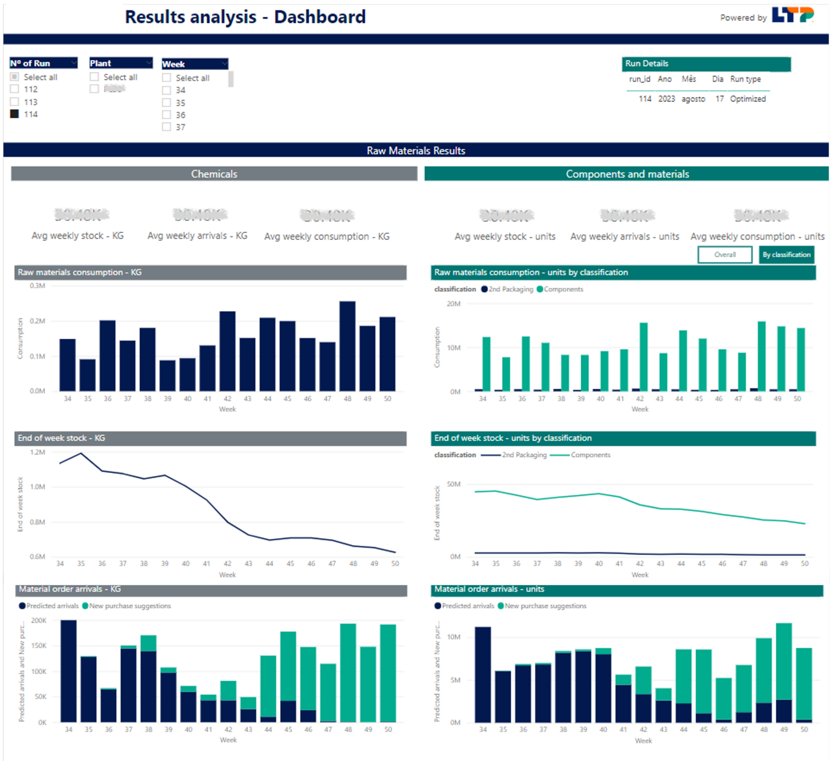


Figure 60: Raw materials view

As the name suggests, the Comparison view is designed to simplify the process of contrasting two separate optimized plans. This view enables an easy side-by-side analysis of KPIs associated to each plan. These KPIs encompass metrics like the count of orders encompassed within the plan, along with the numbers of orders that have been anticipated, postponed, or cancelled. Moreover, the Comparison view provides a comprehensive view of overall expenses, capacity considerations, as well as the operational working schedules for both the entire factories and individual filling lines. This feature-rich view proves invaluable in making informed decisions by presenting a clear comparison between the two plans, aiding in identifying strengths, weaknesses, and areas for potential optimization. The Comparison view is presented in Figure 61.

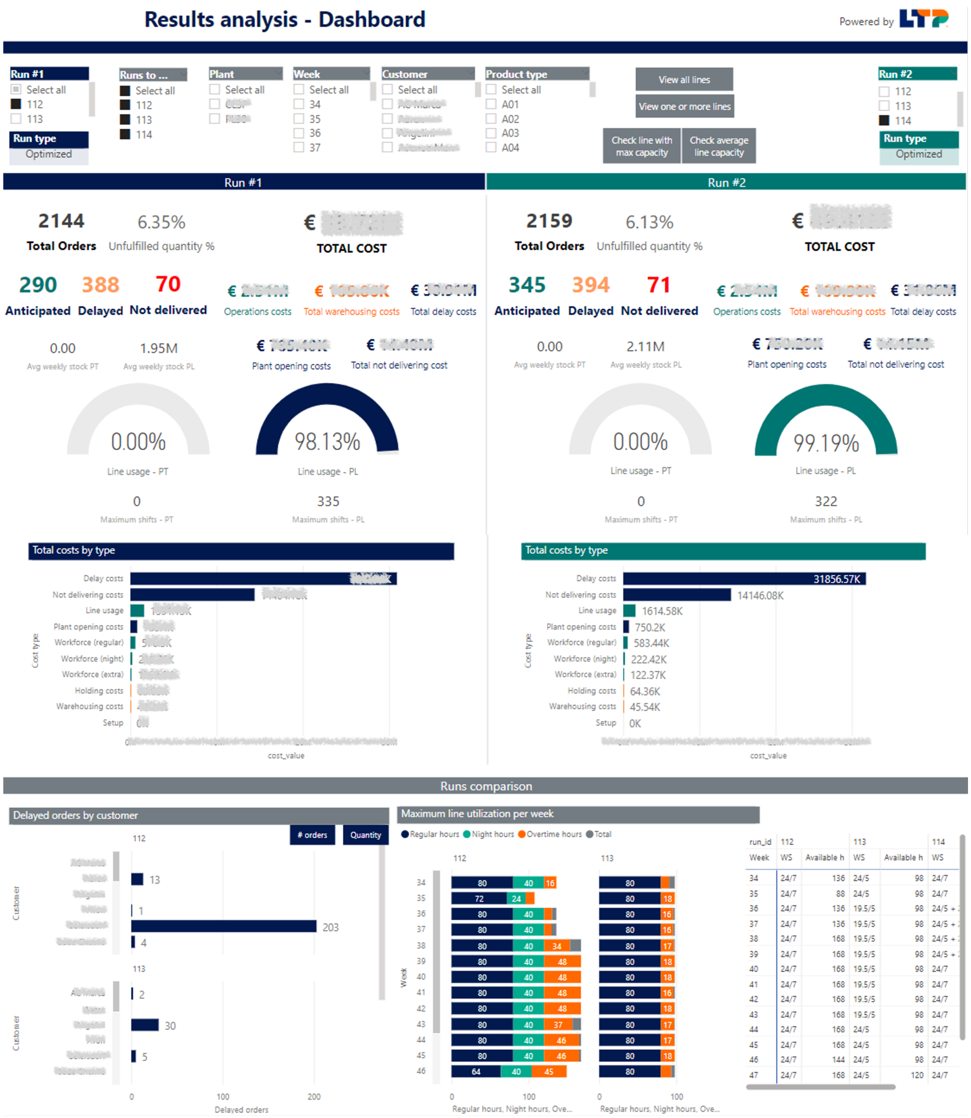


Figure 61: Comparison view