Impact of "Minimum Life on Receipt" on the production of food consumer goods

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Master's Dissertation

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Abstract

Supply chain sustainability has for long been a studied topic. Reducing inefficiencies and waste levels generated has been a fundamental aspect of that effort, with the supply chain of perishable products being one of the main targets. Notwithstanding, many of these attempts focus on players downstream of the supply chain, namely retailers and final consumers, with the contribution of the producer being commonly disregarded.

Producers are subjected to many constraints. One of those is the "Minimum life on receipt" criterion (MLOR), which aims to reduce waste generated downstream the supply chain at the hands of retailers and households. This criterion imposes that products must be delivered with a given lifetime remaining until expiration. Despite being essential to retailers, a strict MLOR can harm the producer, compromising overall supply chain sustainability. Hence, in this dissertation, the impact that this criterion has on the producer is evaluated. Furthermore, the influence that product characteristics have on MLOR impact is also analyzed.

In this dissertation, a production planning problem is tackled to measure the impact that different MLOR values have on the producer. A Mixed Integer Linear Programming Model is adapted from the literature. Four real recipes and twelve other artificial recipes are considered in the experiment, each with distinctive characteristics in what concerns shelf-life, demand patterns, setup expenditure, and number of SKUs. Besides, three different MLOR scenarios are considered in the analysis. The impact of this criterion is determined based on costs and waste generated. Results show that a more flexible value is beneficial for the producer and that product characteristics influence MLOR's impact differently. MLOR has a significant impact on recipes with low annual production volumes that require significant setup activities. MLOR, on the other hand, has a negligible impact on recipes with large annual production volumes. In general, cost minimization and waste reduction are concurrent goals.

As a final remark, this work is a pioneering study on the impact of MLOR on the producer. The main objective is to lay the foundations for future studies on the topic.

Keywords: MLOR; perishable products; supply chain.

Resumo

A sustentabilidade da cadeia de abastecimento é um tema abordado por diversos trabalhos. A redução das ineficiências e do desperdício gerado, tem sido um um dos focos, com a cadeia de abastecimento de produtos perecíveis sendo um dos principais alvos. Não obstante, muitas destas tentativas concentram-se nos intervenientes a jusante da cadeia de abastecimento, nomeadamente retalhistas e consumidores finais, sendo a contribuição do produtor geralmente ignorada.

Os produtores estão sujeitos a várias restrições. Uma delas é o critério MLOR, que visa reduzir o desperdício produzido a jusante da cadeia de abastecimento pelos retalhistas e pelos consumidores finais. Este critério impõe que os produtos devem ser entregues com um determinado tempo de vida restante até atingirem o fim da sua validade. Apesar de ser essencial para os retalhistas, um MLOR rigoroso pode prejudicar o produtor, comprometendo a sustentabilidade global da cadeia de abastecimento. Assim, nesta dissertação, é avaliado o impacto que este critério tem sobre o produtor. Além disso, é também analisada a influência que as características do produto têm sobre o impacto do MLOR.

Nesta dissertação, é abordado um problema de planeamento da produção para medir o impacto que diferentes valores do critério MLOR têm sobre o produtor. Um Modelo de Programação Linear Inteira Mista é adaptado da literatura. Quatro receitas reais e doze receitas artificiais são consideradas na experiência, cada uma com características únicas no que diz respeito ao prazo de validade, volume de produção, custos de setup e número de SKUs. Além disso, três cenários com diferentes valores para o critério MLOR são considerados na análise. O impacto deste critério é determinado com base nos custos e desperdício gerados. Os resultados mostram que um valor mais flexível é benéfico para o produtor e que as características do produto influenciam o impacto do MLOR de forma diferente. O MLOR tem um impacto significativo em receitas com baixos volumes de produção anual que requerem actividades de setup significativas. Por outro lado, tem um impacto negligenciável em receitas com grandes volumes de produção anual. Em geral, a minimização de custos e a redução do desperdício são objetivos convergentes.

Como nota final, este trabalho é um estudo pioneiro sobre o impacto do MLOR no produtor. O principal objetivo é lançar as bases para futuros estudos sobre o tema.

Palavras-chave: MLOR; produtos perecíveis; cadeia de abastecimento.

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"To my grandfather and my role model, Avô Zé"

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Chapter 1

Introduction

Recently sustainability has become a critical factor of supply chain management. Sustainable Supply Chain Management (SSCM) has been a significant focus for businesses since it transforms the whole value chain and consumer behavior. The adoption of new sustainable practices is no more a choice or an option but a necessity. The supply chain of perishable products is one of the main targets when addressing sustainability, where the partners have a shared responsibility of minimizing quality losses to deliver high-quality products to the end consumer (Saidi et al., 2020).

Despite all these efforts towards sustainability, a large portion of what is produced is never consumed. The Food and Agricultural Organisation of the United Nations (FAO) estimates that about one-third of the food produced worldwide is wasted along the supply chain (Gustavsson et al., 2011). With these figures in mind, it is important to distinguish between food loss and food waste. The former refers to the decrease in edible food mass at the production, post-harvest, and processing stages of the food chain, due to processes such as weight loss, microbial rots, diseases, and insect damage. Alternatively, the latter refers to the discard of products not meeting set quality standards, waste generated during processing, surpluses during catering and consumption, and unsold volumes running out of shelf life owing to a mismatch between supply and demand (Hertog et al., 2014). For this thesis, food waste is the one of interest. Wasting large portions of food causes significant global problems in different areas. Firstly, wasting food while millions of people are suffering from hunger raises moral questions. Secondly, food production consumes scarce resources, leads to environmental degradation, contributes to animal suffering in vain if food is wasted. Thirdly, wasting food has a significant economic impact, especially for consumers, who spend significant amounts of money on food, wasted in the households (Eriksson et al., 2014).

A Waste and Resource Action Programme (WRAP) study presents some measures to reduce food waste by extending shelf life. One of the suggestions of this study is revising the definition of the Minimum Life on Receipt (MLOR) used by retailers. The point of receipt of the product at a retailer's depot marks a pivotal point in the supply chain, at which the remaining life of the product is monitored. It represents the interface between the producer and the retailer and is considered a control point where quality standards are checked. The MLOR criterion imposes that a particular product can only be accepted in this stage of the supply chain if the remaining life of the product is above a given threshold. In WRAP's study, an extension of this criterion is proposed to decrease the waste generated at retailers and households (Lee et al., 2015). When a tight MLOR is established, which means that products need to be delivered with a longer remaining life until the expiry date, the products received at retailers have an increased available lifetime that is conveyed to the end consumer, reducing waste. However, if this criterion is too tight, producers may encounter difficult hurdles to overcome. The first is that many of the products delivered may not be accepted on retailers' sites by not complying with the established MLOR. The second is the hard-to-meet constraints that force producers to plan production inefficiently, increasing waste in the middle of the supply chain. Therefore, a collaborative definition of this criterion tailored to the different situations would allow for better outcomes when considering food waste.

1.1 Motivation

A traditional supply chain is composed of several players that act together to deliver end products or services to final consumers. Managing the relations between the different stakeholders is a challenging endeavor. Since production planning decisions taken in this stage have a great impact downstream the supply chain, the producer plays a key role.

The production lot sizing and scheduling typically needs to consider various pieces of information in the planning time horizon simultaneously, such as an extensive number of stock-keeping units (SKUs) to be produced with different demands, several machines with different capacities and specificities, more than one production stage involving sequence-dependent setup times and costs, production synchronization of the stages, intermediate product storage, among others (Baldo et al., 2014). Furthermore, perishability-related constraints must be considered in many industries to devise efficient production plans compliant with the established requirements. The MLOR criterion is one of those responsible for the increased planning complexity in these settings.

Given the great number of SKUs handled by retailers, the received products need to comply strictly with the pre-established MLOR to be accepted. When producers fail to meet this criterion, the products have to be returned to their origin. Even in situations where the products are not sent to the retailer, the producer is responsible for the disposal process, which entails increased costs. When possible, agreements are reached for the non-complying products, applying discounted prices, which unequivocally result in decreased profits for the producer.

Furthermore, the MLOR criterion pushes production towards smaller lot sizes and more frequent production of the different items, often resulting in inefficiencies. In many industries with high setup costs, imposing a higher MLOR may be challenging due to higher sterilization and cleaning costs and increased losses in processing operations.

Bearing this in mind, this dissertation focuses on studying the impact that different values of the MLOR criterion have on the producer in terms of waste and costs. It is also desired to validate if an indistinct definition of this criterion is the most suitable approach. It is expected that a decrease in MLOR for certain products allows for more efficient production and increased supply chain sustainability.

Presently, retailers require a MLOR of ⅔ of the shelf life, regardless of the product considered. Despite being a manageable value for most products, it may raise obstacles for others, leading to disruptions in the supply chain.

A production planning model that accounts for variations in MLOR will be developed to evaluate the impact on costs and food wastage. As far as the author's knowledge, it is the first study on the impact of MLOR from the producer perspective.

1.2 Mobfood

MobFood is a research and development project that emerged from the ambition of several agents of the agri-food sector to address the challenges faced by the Portuguese food industry on the way to becoming more competitive. The project aims to promote cooperation between enterprises and research institutions in three main areas: Food Safety and Sustainability, Food for Health and Well-being, and Quality and Safe Food Production. MobFood seeks to have a food industry that manages resources efficiently and is sustainable, interlinked, transparent, resilient, safe, and consumer-centric. The project is divided into eight PPS (product-process-service) projects that are developed independently. This work is part of the PPS 7, which aims to develop a collaborative and sustainable food supply chain. It was in this context that the topic of MLOR arose.

1.3 Research Problem

This dissertation proposes to tackle a problem faced by many producers: the definition of the most suitable value for the MLOR criterion by measuring the impact that variations of the latter have on food waste and costs. Retailers usually require indiscriminately that products have at least ⅔ of their shelf-life remaining at the point of receipt. Due to a large number of suppliers for the same product, retailers can be rigid and ambitious in the definition of the MLOR criterion, rejecting every non-compliant product. As a result of the increasing retailer's power, producers might be forced to agree with conditions that constrain the production process leading to inefficiencies and increased levels of waste.

The main issue is that variations in the MLOR criterion value have opposite effects on the different supply chain players. While an increase in its value favors retailers and undermines producers, reducing it benefits producers and constrains retailers' operations. Having this in mind, one of the solutions goes through the adoption of a collaborative strategy, where the definition of the criterion is tailored to each specific situation having in mind all players' interests.

Rather than defining the MLOR value indistinctly for every product, it should consider product features, as shelf-life and product demand characteristics, and production-related features like the production costs associated. Only thus can the interests of every player of the supply chain be attained.

In order to put into practice such strategies, the impact of changes in the MLOR criterion on the producer must be measured. Hence, the main goal of this thesis is to study if a tailored definition of the MLOR criterion, based on product and process features, is beneficial in what concerns costs and waste while trying to identify situations in which it should be applied. For that matter, a producer of processed food products is used as a case study. Although this criterion has greater prominence in products with shorter lifetimes, the producer felt that an analysis of the impact of this criterion on products with longer lifetimes ought to be conducted due to the constraints imposed on the production process.

1.4 Methodology

The first step of this dissertation is related to mapping the producer's operations and defining the project's scope. Afterward, based on the previously mapped processes, an existing production planning model in the literature is adapted to fit the specific constraints of the problem at hand. In the following stage, the model is fed with real data from real recipes and SKUs produced by the producer and artificial variations of the previous to cover all possibilities, meaning that each of the analyzed recipes intends to mimic a recipe with unique characteristics. To run the model, a math programming solver, Gurobi 9.1.2, is used. The recipes in the analysis have different shelf-lives, different demand characteristics, and different production costs associated, allowing for a multi-dimensional analysis of the impact of MLOR.

Based on the results obtained, conclusions are withdrawn regarding the impact on costs and waste that the MLOR criterion value changes entail.

1.5 Structure

This dissertation is divided into five chapters. The next chapter is the Literature Review, where it is presented the theoretical background and state of the art in what concerns production planning models accounting for perishability. In Chapter 3, the problem addressed in this dissertation is described and the model in use to solve the problem is outlined with the respective assumptions and simplifications. Chapter 4 details the simulation experiment and the results obtained. Ultimately, Chapter 5 presents the conclusions of this dissertation and further research possibilities.

Chapter 2

Literature Review

This chapter is divided into four sections. The first section outlines the different classifications adopted to define perishability. Then, different time scales that can be employed when modeling a production planning problem are presented. The last two sections review different works on production planning considering perishability constraints, with the last section focusing specifically on multi-stage industries.

2.1 Classifying Perishability

Identifying and characterizing perishable supply chains is a challenging endeavor since perishability can occur in a varied range of situations and has a blurry definition. Throughout the years, different classifications of perishability were proposed, some of them complementary and others contradictory (Amorim et al., 2013).

The analysis on deterioration was first approached in Whitin (1957) stating the loss of value fashion products suffer after some storage period. This deterioration is related to the perceived loss of value by the consumer and not with the physical deterioration of the item. With that in mind, Ghare and Schrader (1963) divide product deterioration into direct spoilage, physical depletion, and obsolescence. Direct spoilage is characterized by damage, spoilage, vaporization, or dryness of the goods, e.g., flowers and fresh food. Physical depletion concerns the products that evaporate quickly, therefore, losing their potential, e.g., alcohol. Obsolescence is the terminology used when referring to products that lose value while their properties remain unchanged, e.g., newspapers and radioactive products.

In Nahmias (1982), a review on ordering policies of perishable inventories, the author differentiates products regarding their lifetime in two different groups: (1) products with fixed lifetime and (2) random lifetime. This categorization is related to the ability to know beforehand the lifetime of the product. Items such as milk and blood have fixed lifetimes, while fruits and vegetables have random lifetimes.

Raafat (1991) classifies deteriorating items in three different groups according to time and value of the inventory. The first refers to constant-utility perishable goods, whose value remains constant, while product decays until the end of the usage period, e.g., liquid medicine. The second concerns decreasing-utility perishable goods, which lose value over time, e.g., fresh food, and the third considers increasing-utility perishable goods whose value increases over time, e.g., wine.

Ferguson and Koenigsberg (2007) work on managing deteriorating inventories, separates goods into three types according to the perceived quality level of the aged product by the consumer. The first refers to products whose perceived quality does not degrade over time but has a usage period, e.g., hotel rooms. The second type refers to products whose perceived quality keeps decreasing until it reaches zero when a new version of the product is launched, e.g., newspapers and weather forecasts. The third is similar to the second, with products having a deteriorating perceived quality level. Nevertheless, it does not reach zero when a new version of the product is launched. This third group can be divided into two main categories: (1) decreasing functionality products where functionality deteriorates over time, e.g., fruits and vegetables, and (2) non-decreasing functionality where functionality does not degrade over time, but the customers' perceived utility of these products deteriorates, e.g., fashionable clothing and high technology products with short life cycles.

Lin et al. (2006) separates deterioration into two groups: (1) age-dependent on-going deterioration, e.g., vegetables and fruits, and (2) age-independent on-going deterioration, e.g., volatile liquids, considering that the deterioration process starts after production. Although suffering natural attrition, it is difficult to find a connection between age and perishability in the second group of products. In a similar analysis, Bakker et al. (2012) mentions two types of products: (1) age-dependent deterioration rate products, meaning that the lifetime of the product follows a probabilistic distribution and (2) products with time or inventory deterioration rate.

In Pahl and Voß (2014), a clear distinction between perishable goods that cannot be used anymore and lose all their utility at once after a certain point in time, and items subject to deterioration that lose their utility gradually is presented. These differences are shown in Figure 2.1. On the left is shown the abruptness of perishability in opposition to the gradual discrete treatment of deterioration in the second graph. The third graph displays the possible courses of continuous deterioration, and the fourth unveils three possible time intervals regarding the quality decrease of items that can be reworked. The first interval describes the moment when items present regular quality until rework is needed, thereby initializing the second stage. The third describes the moment after the lifetime of the item has been achieved.

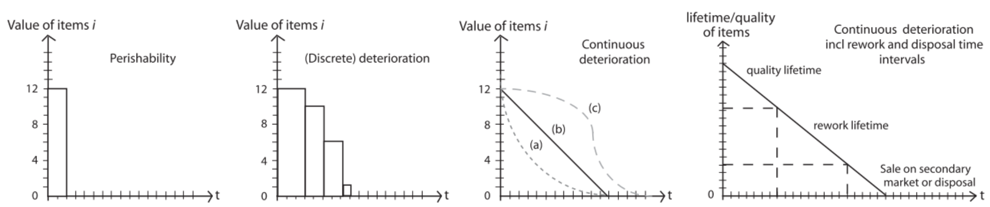


Figure 2.1: Courses of perishability and deterioration Pahl and Voß (2014)

Chaudhary et al. (2018), in an attempt to aggregate the different classifications on perishability stated above, separate the decay pattern for inventory models into five main categories that may overlap with each other: (1) models with fixed lifetime, (2) models with random lifetime, (3) models with time-dependent deterioration rate, (4) models with inventory-dependent deterioration rate and (5) models with age-dependent deterioration rate. Products with deterministic shelf-life are fixed lifetime products and should be disposed when they are outside the product's lifetime, e.g., Human Blood. A random lifetime product is one whose lifetime is not predetermined while in stock. Vegetables and fresh fruits are examples of this type of product whose decay rate is uncertain and considered a random variable. Items with a time-dependent deterioration rate can decay either continuously or discretely with time. Recent research shows that more and more studies have considered an interdependence between deterioration rate and time. Regarding products with an inventory-dependent deterioration rate, the level of inventory in hand affects items' decay. In items such as bananas, due to collision and self-contact, the stock deterioration is increased (Maity and Maiti, 2009). The last category refers to age-dependent deterioration where the product's lifetime is assumed to be a random variable.

Considering that classifications on perishability are usually tailored for a specific purpose, Amorim et al. (2013) propose a unified framework to classify perishability that allows an exhaustive classification through connecting different perspectives of the same phenomenon. The suggested framework is composed of three classifying dimensions (1) Physical Product Deterioration, (2) Authority Limits, and (3) Customer Value, which are strictly linked with three different perspectives of the perishability phenomenon: Product, Authority and Customer. The first dimension, the Physical Product Deterioration, reflects if the good suffers physical modification through spoilage, decay, or depletion. The second dimension, the Customer Value, is related to the loss of value associated with a given product and reflects the willingness to pay for a particular good throughout its lifetime. Newspapers are a representative example of products that do not suffer physical deterioration but decrease their value from the consumer perspective. The third dimension is concerned with the Authority Limits and represents the external regulations that directly influence the perishability phenomenon. These limits come from a varied set of reasons, such as customer safety or better information conveyed to the consumer. This framework's relevance, which considers the different dimensions of perishability, is substantial since it is essential to tackle the planning problem one may face explicitly. The mathematical model would need to capture these different dimensions in order to control the issues perishability entails.

For this work, emphasis is placed on products with fixed authority limits that suffer physical deterioration. With this in mind, it is important to introduce the definition of the concept of shelf-life. Amorim et al. (2013) define shelf-life as the period after manufacturing during which the manufactured product is of satisfactory quality. In other words, it is the period that a product can remain in a saleable condition. Shelf-life is closely related to the authority limits dimension rather than the physical deterioration dimension of the product, which means that many products may be in good physical condition even after their shelf-life has ended.

2.2 Time scale selection

When developing a production planning model, one of the dimensions to consider is the time scale used.

In Camargo et al. (2012), the authors state that the choice of an appropriate time scale (discrete or continuous) when modeling the problem depends on the inside dynamics of the production that is being modeled. In addition, a distinction between both time scales is presented. Discrete-time representation obliges decisions and events that occur in continuous time to be translated into decisions and events occurring according to discrete time scale. The planning horizon is partitioned into periods, and the production is confined to the grid of time periods.

There are two types of models: large bucket and small bucket. In large bucket models, the planning horizon is divided into a small number of long periods representing, in most cases, a week or a month. This way, it is possible to perform several setups per period, and sequencing decisions are made through decision variables similar to those of routing problem formulations. In small bucket models, the planning horizon is partitioned into many short periods, usually referred to as micro-periods, where at most one setup may be performed, and the production sequence comes from the setup state change among adjacent micro-periods (Guimarães et al., 2014). The downside of the small bucket approach is that they require an excessively high number of periods for real-world instances, especially for mathematical programming approaches.

Discrete-time formulations provide a reference time-grid for all shared resources. Hence, material balances between production stages, inventory and backlog levels, and availability and consumption of utilities can be monitored and modeled without the introduction of any non-linearities. Besides, recent studies show that discrete-time representation leads to solutions with increased quality (Georgiadis et al., 2021). However, this bucket orientation of discrete-time models raises some obstacles. The main one is to address continuous-time settings such as events that may cross over time boundaries. Discrete formulations lead to very large and often intractable models, especially when small discretization of time is required (Georgiadis et al., 2019).

In opposition to discrete-time representation, in continuous time models, the production occurs at any point in time in the planning horizon, overcoming discrete-time limitations. The planning horizon is divided into a given number of events. However, continuous models suffer from large integrality gaps and do not allow to incorporate holding costs easily. Hybrid continuous-discrete time-oriented models are a possibility to minimize the downsides of each type (Camargo et al., 2012). A discrete-time formulation is used in this thesis, relying on a mixture of large and small time buckets. This two-level time structure is critical to achieve two distinct objectives of the problem. On the one hand, with the large bucket time structure, it is possible to control the perishability dimension and demand. On the other hand, the small bucket time structure allows the needed flexibility to handle production scheduling.

2.3 Production planning handling perishability

Most of the production planning literature assumes that finished and intermediate products have unlimited lifespans, meaning that they can be stored and used indefinitely. However, in many industries, deterioration and loss of value over time are common, which forces production planning models to consider this product dimension. Furthermore, perishable goods literature is mainly focused on inventory management, pricing, and reverse logistics (Acevedo-Ojeda et al., 2020). In Amorim et al. (2013) the authors recognize that perishability enforces specific constraints on a set of crucial production planning decisions. They consider that production planning tasks encompass lot-sizing decisions and scheduling decisions. Lot sizing consists of deciding the size of the lots to be produced, trading off the changeover and stock holding costs, and scheduling to decide when to produce each of those lots.

The production planning models under analysis may focus on lot-sizing or scheduling exclusively or attain both dimensions simultaneously. In Pahl and Voß (2014) review on production and supply chain planning, two main approaches to incorporate perishability are presented. The first assumes a loss of a portion of inventory modeled by an exponential shrinkage factor. This first approach is mainly used in optimization models that seek to derive optimal replenishment quantities and time lengths between orders assuming that all products suffer the same deterioration. Nevertheless, this assumption is limiting if we want to create planning models that should avoid deterioration in the first place. Thus, the second approach is based on avoiding inventory expiration by limiting the number of periods of production, this way guaranteeing that products do not reach the end of their shelf-life (Acevedo-Ojeda et al., 2020).

In the field of lot-sizing (LS), Hsu (2000) presents an uncapacitated, single-item lot-sizing problem considering age-dependent inventory costs with a deterioration rate factor. This problem is tackled and generalized in Hsu (2003), allowing for backlogging. In Sargut and Işık (2017) an extension to this model is developed considering capacity constraints. Wang et al. (2009) presents an integrated model for simultaneously optimizing the production batch size and batch dispersion policy in a food manufacturing context by incorporating traceability.

In the field of scheduling considering perishability, most of the work developed considers perishability by adding shelf-life constraints to the Economic Lot Scheduling Problem (ELSP) (Amorim et al., 2013). Yao and Huang (2005) introduce an extension to the traditional ELSP by considering multiple continuously deteriorating items where each of the previous deteriorates at an exponential rate without the possibility of being repaired. Similarly, Lin et al. (2006) develop a multi-item production-inventory problem where each product is assumed to have a significant rate of deterioration. It is considered an exponential deterioration rate and a constant inventory shrinkage factor.

Considering the scope of this dissertation, models that consider lot sizing and scheduling decisions simultaneously are of greater interest. For that matter, Neumann et al. (2002) proposed a new solution approach for batch production problems. This approach consists of a decomposition of production scheduling in batching and batch scheduling. The batching problem transforms the primary requirements for products into individual batches, where the workload is to be minimized. Then the batch scheduling problem allocates the batches to scarce resources where some regular objective function like the makespan is to be minimized. In this approach, perishable intermediate products cannot be stored being consumed without delay. Chen and Chen (2006) propose a mathematics-based decision model that tackles lot-sizing and scheduling decisions taking into account the dynamic aspect of customer demand and marketing planning, the deteriorating property of a production item modeled by a deteriorating coefficient, and the restriction of finite capacity. Demand and production are dependent on the selling price. Pahl and Voß (2010) and Pahl et al. (2011) extend well-known discrete lot sizing and scheduling models by including deterioration and perishability constraints. This approach does not restrict the number of periods for production, allowing inventory expiration, but penalizes it by applying a disposal cost. The second work is an extension that includes sequence-dependent setup times and costs. Amorim et al. (2011), considering the necessity to attain both cost minimization and product freshness maximization, present multi-objective lot sizing and scheduling mixed-integer programming models for a make-to-order and a hybrid make-to-stock/make-to-order production strategy. A hybrid genetic algorithm is developed. The make-to-order model developed in Amorim et al. (2011) is the one adopted in this dissertation.

2.4 Production planning on multi-stage industries handling perishability

Despite the work developed regarding production planning in a perishable setting, different aspects have not received sufficient attention. There is room for more exhaustive studies on multi-level structures of production processes incorporating lifetime constraints (Pahl and Voß, 2014). In Wei et al. (2019), the authors review the literature on this topic. In Entrup et al. (2005), Mixed Integer Linear Programming models that integrate shelf-life issues into production planning and scheduling are developed. The research is based on an industrial case study of yogurt multi-stage production. Relying on the principle of block planning, three different MILP models for weekly production planning are presented that apply a combination of a discrete and continuous representation of time. Although yogurt production is a two-stage process, the fermentation stage is only considered in the model by a capacity restriction and by imposing minimum batch sizes for the packaging lines. Van Elzakker et al. (2014) consider shelf-life restrictions in fast moving consumer goods industry. The production process is a two-stage make and pack process where either stage could be the bottleneck. Shelf-life restrictions are introduced either by measuring the age of the products directly or by forcing products to leave inventory before they reach the end of their shelf-life. Leung et al. (2007) study a two-level production process for perishable products (toys). The end products are perishable given that after a certain time they become obsolete. In this study, a postponement concept to produce semi-finished products in a given time and transfer semi-finished products to finished products in the following periods is applied. In Wei et al. (2019), the authors recognize that there is still a gap introducing the shelf-life monitoring (especially of intermediate materials) for multi-level production planning in process industries and propose a model which incorporates materials' shelf-lives at different stages of the production process. An extension of the classical multi-level lot-sizing and scheduling problem formulation (MLGLSP) is presented by adding perishability constraints to raw materials, intermediate, and end products. Acevedo-Ojeda et al. (2020) develop three MILP formulation variants of the two-level lot-sizing problem incorporating different types of raw material perishability: (1) fixed shelf-life, (2) functionality deterioration, and (3) functionality-volume deterioration. For that purpose, the authors consider a production system with one item to be produced (finished product) and another item to be procured from a supplier (raw material).

Chapter 3

Problem Description and Methodology

This chapter is divided into two sections. In the first section, the problem in analysis is described, and in the second section, the model developed to replicate the operations of the producer and the assumptions considered are outlined.

3.1 Operations of the producer of processed food items

A producer of processed food items is used as a case study for this dissertation. The company produces a wide variety of products with different characteristics in what concerns shelf-lives, demand patterns, packaging, and production costs. The production process is divided into two stages, where a packaging stage follows a semi-continuous stage. In the literature, this type of production is referred to as "make-and-pack" production. The different recipes are produced in large reactors in the first stage, being then directed to storage tanks used as buffers. Afterward, following the production plan, the produce is forwarded to the packaging lines. In this type of production process a large number of products (SKUs) is produced from a few initial product recipes.

The plant has great flexibility, enabling almost entirely the connection between all reactors, storage tanks, and packaging lines. Typically the products are assigned to the packaging lines based on the package format regardless of the recipe.

The aforementioned aspects of the production process demand from the producer a considerable planning effort to guarantee that demand is fulfilled sustainably and efficiently while assuring high customer satisfaction. Despite the abovementioned diversity, many restrictions to which the production is subjected are defined indiscriminately, namely the MLOR. This criterion imposes that products must be delivered with at least ⅔ of the shelf-life remaining in order to be accepted downstream the supply chain by retailers. Thus, the company felt that an analysis on the impact of MLOR ought to be conducted, notably in the impact that variations of this criterion might induce. Although this criterion has more relevance for fresh products with short shelf-lives, the producer felt that it also restricts longer shelf-life products.

Due to this restriction, the producer is forced towards more frequent production of the different items and smaller lot sizes, which in some situations might impact costs and waste negatively while in others might be neutral, with product characteristics playing a pivotal role in the outcome.

Shelf-life is one of those characteristics. For products with a short shelf-life, like dairy products, a tight MLOR value is vital to guarantee that waste downstream the supply chain is diminished. Notwithstanding, the analyzed products in this dissertation have long shelf-lives ranging from four months to ten years, allowing for a more flexible definition of the criterion. For instance, a product with a shelf-life of one year ought to be delivered with eight months of shelf-life remaining. A revision of the criterion in similar situations would allow for a more sustainable supply chain as a whole without damaging the players individually.

Another critical dimension to consider is linked with the production costs. A significant portion of the costs incurred by the producer is associated with cleaning and sterilization operations. While some recipes are similar and do not oblige significant cleaning operations between production runs, others are distinct and entail significant setup inefficiencies. For the latter, a tight MLOR value that forces more frequent production events is harmful, forcing avoidable costs. Apart from the increased expenditure, it is also critical to consider the waste levels that such criterion generates. More frequent productions mean unequivocally smaller lot sizes. Since wastage generated in the processing stages due to cleaning and sterilization operations is independent of the volume produced, that is to say, that the waste generated in absolute terms in each cleaning operation is immutably the same, lower production volumes lead to a higher percentage of lost resources. With this in mind, further improvements are still possible.

The demand pattern of the products is another attribute to consider. Given the wide variety of recipes and products produced by the producer of processed food items, a close look should be given to this dimension. Some recipes demand frequent production due to the large number of units produced yearly, while others, where the production volume is lower, allow for fewer production events. As stated before, lower production volumes entail increased relative levels of waste, making products with such characteristics a focal point of the analysis to be performed. For these products and with a more flexible MLOR value, the number of production runs could be reduced significantly with the waste generated following the same course. For instance, a recipe that presently is produced four times a year could be produced in only two or three production events, decreasing waste similarly.

The goal of this thesis is to grasp all this variability among the recipes and SKU's produced and attempt to withdraw conclusions regarding the costs and waste generated, in an effort towards a sustainable, resilient, and consumer-centric supply chain, while advocating for the advantages of a collaborative attempt amid the different stakeholders of the supply chain.

3.2 Modeling the problem

One possible strategy to evaluate the impact of the MLOR for the producer consists in developing a production planning model, which in turn incorporates the criterion, intending to analyze the impact that variations of the former generate. For that matter, a Mixed Integer Linear Programming model is adapted from the literature. The model is implemented using Python as a modeling environment, and the optimization software is Gurobi 9.1.2.

3.2.1 Assumptions of the problem

Given the great flexibility of the production process, there are some dimensions that the model is unable to capture. Thus, some assumptions have to be made. The following assumptions are considered:

- Despite being a make-and-pack production, in this model the focus is only on the packaging stage since it is the bottleneck and the one of relevance in what concerns perishability;
- The semi-continuous production stage is incorporated by imposing a minimum and maximum batch size;
- Shelf-life begins at the moment the product is packaged;
- Products belonging to the same recipe have an equal shelf-life period;
- The quality of the product remains unchanged until its lifetime is reached;
- There is no possibility of manufacturing products that do not comply with the MLOR criterion;
- The MLOR verification is carried at the point of receipt;
- Products are produced based on specific demand orders (make-to-order strategy);
- Waste generated depends on the reactor used for production;
- Setup state carryover is not allowed between productions days;
- Setup operations between recipes and packaging formats can not be done in parallel.

3.2.2 Building the model

To analyze the impact of MLOR on the producer, a production planning model is adapted from the literature. Amorim et al. (2011) developed a multi-objective lot-sizing and scheduling model, assuming a make-to-order production strategy and attaining the goal of cost minimization and product freshness maximization simultaneously. In this model, demand elements have associated a number of production quantities and the corresponding production day, allowing to model the perishability phenomena accurately. Among the most significant adaptations made are the integration of MLOR and inventory holding costs in the model. Considering the specific characteristics of the problem in hand the adapted model is described below.

3.2.2.1 Model

All product variants $k = 1,...,K$ based on the same recipe form a block; therefore, a product can be assigned to one block only. Blocks $j = 1,...,N$ are to be scheduled on $l = 1,...,L$ parallel production lines over a finite planning horizon consisting of macro-periods $d = 1,...,T$ with a given length. The scheduling takes into account that the setup time and cost between blocks is not bound up to the sequence but with the block itself. When changing the production between two products that are variants of the same recipe, a sequence-independent setup is also performed.

A macro-period, in this case a day, is divided into a fixed number of non overlapping micro-periods with variable length. Because the production lines can be scheduled independently, this is done for each line separately. S_{ld} denotes the set of micro-periods s belonging to macro-period d and production line l. The length of a micro-period is a decision variable, which is expressed by the production of several products of one block produced in the micro-period on a line. A sequence of consecutive micro-periods, where the same block is produced on the same line, defines the lot of a given block, and the quantity of the products from that recipe produced during these micro-periods defines the size of the lot. Therefore, a lot may aggregate several products from a given block and may continue over several micro-periods. The number of micro-periods of each day defines the upper bound on the number of blocks to be produced daily on each line. Consider the following indices, parameters, and decision variables.

Sets

l	=	parallel production lines
i, j	=	blocks
k	=	products
d, h	=	macro-periods
s	=	micro-periods

Parameters

K_j	=	set of products belonging to block j
$\|K_j\|$	=	number of products belonging to block j
S_{ld}	=	set of micro-periods s within macro-period d and line l
Cap	=	capacity (time) of each production line
a_k	=	capacity consumption (time) needed to produce one unit of product k
c_k	=	production costs of product k (per unit)
u_k	=	shelf life duration of product k after completion of its production (time)
m_j	=	minimum lot size (kg) of block j
$scb_{lj}(stb_{lj})$	=	sequence-independent setup cost (time) of a changeover to block j on line l
$scp_{lk}(stp_{lk})$	=	sequence-independent setup cost (time) of a changeover to product k on line l
scr_j	=	sequence-independent setup cost of a changeover to block j in the reactor

d_{kd}	=	certain demand for product k in macro-period d (units)
t_{ls}	=	equals 1, if a line l in a micro-period s is unavailable for production
$MLOR$	=	minimum life on receipt
M_j	=	maximum lot size (kg) of Block j
pw_k	=	weight of product k (per unit)
H	=	inventory holding costs per day (function of the production costs)

Decision Variables

w_{khd}	=	fraction of demand of product k produced in macro-period h for meeting demand in micro-period d, $\forall d \geq h \wedge d \leq h + u_k(1 - MLOR)$
q_{lks}	=	quantity of product k produced in micro-period s on line l
y_{ljs}	=	setup state:y_{ljs} = 1, if line l is set up for block j in micro-period s (0 otherwise)
p_{lks}	=	setup state:p_{lks} = 1, if line l is set up for product k in micro-period s (0 otherwise)
z_{ljs}	=	takes on 1, if a changeover to block j takes place on line l at the beginning of micro-period s (0 otherwise)
r_{jd}	=	reactor setup state: r_{jd} =1, if the reactor is set up for block j in macro-period d

Objective

$$\min \sum_{l,j,s} scb_{lj} \cdot z_{ljs} + \sum_{l,k,s} scp_{lk} \cdot p_{lks} + \sum_{j,d} scr_j \cdot r_{jd} + \sum_{k,h,d} (d-h) \cdot w_{khd} \cdot d_{kd} \cdot H \cdot c_k \tag{3.1}$$

Constraints

$$\sum_h w_{khd} = 1 \qquad \forall k,d : d_{k,d} > 0 \tag{3.2}$$

$$\sum_h w_{khd} = 0 \qquad \forall k,d : d_{k,d} = 0 \tag{3.3}$$

$$\sum_{l,s \in S_{lh}} q_{lks} = \sum_d d_{kd} w_{khd} \qquad \forall k,h \tag{3.4}$$

$$\sum_{k \in K_j} p_{lks} \leq y_{ljs} |K_j| \qquad \forall l,s,j \tag{3.5}$$

$$q_{lks} \leq \frac{Cap}{a_k} p_{lks} \qquad \forall l,k,d,s \in S_{ld} \tag{3.6}$$

$$\sum_{j,s \in S_{ld}} stb_{lj} z_{ljs} + \sum_{k,s \in S_{ld}} (stp_{lk} p_{lks} + a_k q_{lks}) \leq Cap \qquad \forall l,d \qquad (3.7)$$

$$\sum_j y_{ljs} + t_{ls} = 1 \qquad \forall l,s \qquad (3.8)$$

$$\sum_{k \in K_j} q_{lks} pw_k \geq m_j (y_{ljs} - y_{l,j,s-1}) \qquad \forall l,j,s \qquad (3.9)$$

$$z_{ljs} \geq y_{li,s-1} + y_{ljs} + t_{l,s-1} - 1 \qquad \forall l,s,i,j : j \neq i \qquad (3.10)$$

$$\sum_{l,k \in K_j, s \in S_{ld}} q_{lks} pw_k \leq M_j \cdot r_{jd} \qquad \forall j,d \qquad (3.11)$$

$$w_{khd}, q_{lks} \geq 0; p_{lks}, y_{ljs}, z_{ljs}, r_{jd} \in \{0,1\} \quad \forall h,d,j,k,l,s \qquad (3.12)$$

It is important to stress that the variable w_{khd} is only instantiated for $d \geq h \wedge d \leq h + u_k(1 - MLOR)$, to ensure that demand fulfilled in period d is produced beforehand with units that comply with the MLOR criterion. It is assumed that stock in the beginning and the end of the planning period is null. Furthermore the last micro-period of each macro-period is unavailable for production precluding setup carryover between consecutive macro-periods. It is assumed that the production in the reactor in a given macro-period goes through the packaging stage in the same macro-period.

In the objective function, production-related costs influenced by MLOR are minimized, namely, sequence-independent setup costs between blocks in the packaging lines, sequence-independent setup costs of products, sequence-independent setup costs of the reactor, and holding costs. Since production costs in a make-to-order strategy are the same regardless of the MLOR value, those costs are not directly considered in the model. In Clendenen and Rinks (1996), holding costs are defined as a percentage of the product cost, with the same being assumed in this thesis.

This model distinguishes between major setups and minor setups, so both are being considered for the first product of a given block. In industries where there is a final bottling stage in the production process, a major setup might correspond to cleaning the lines and linking them to another production tank, while minor setups may correspond to setting the machine to fill the produce in new packages. These operations can not be done in parallel.

Considering the constraints to which the problem is subjected, Constraint (3.2) and Constraint (3.3) match each day demand with specific production done until that day without backlogging. Constraint (3.4) forces total production from each day to meet demand from that day onward in the planning horizon. Constraint (3.5) ensures that a product can only be produced if the correspondent block is set up. Constraint (3.6) assures that a product can only be produced if the machine is set up to produce that product, considering the available capacity. In Constraint (3.7) the capacity of the lines is reduced by the setup times between blocks and products and by the time consumed producing those products. Constraint (3.8) determines that only one block can be produced in a given line and in a given micro-period, provided that the machine is available for production. Constraint (3.9) introduces minimum lot-sizes for each block produced. Constraint (3.10) determines the occurrence of changeovers between blocks and Constraint (3.11) imposes a maximum lot size for a given block guaranteeing that if a given block is produced in a given macro-period there is a setup to be performed in the reactor. Both minimum and maximum batch sizes are set based on the quantities produced in kilograms.

Chapter 4

Results and Discussion

In this chapter, the simulation experiment developed, the different scenarios, and the input parameters considered are presented. Afterward, the results obtained are outlined and analyzed.

4.1 Simulation Experiment

The main objective of this experiment is to grasp the different repercussions that a change in the MLOR value generates in the producer relative to costs and waste. Given the vast number of recipes and SKUs produced by the company, analyzing every recipe would be complex. Instead, a subset of recipes is selected so that the main differences between them are reflected. For that matter, initially, four different scenarios are considered. Each of these four baseline scenarios represent a real recipe, with specific characteristics in shelf-life, demand patterns (production volume), number of SKUs, and production setup costs. Considering these four recipe's characteristics and aiming to measure the impact that each one has on the producer, two levels for each characteristic are contemplated and detailed below. In that regard, twelve artificial recipes are added. The sixteen recipes in the analysis are displayed in Table 4.1. The artificial recipes derive from the baseline ones and allow for an exhaustive analysis.

One of the dimensions considered when defining the recipes in analysis concerns the production volume. Thus, two distinct clusters are devised: (1) recipes produced often with high annual production volumes and (2) recipes with low production volumes. Regarding the number of SKUs, two types of recipes are considered: (1) recipes with a considerable number of SKUs and (2) recipes with only one SKU. Another dimension that differentiates the chosen recipes relates to the setup costs incurred and the ease with which the recipes are scheduled without forcing a setup operation. Some recipes are very similar, meaning that producing them sequentially does not cause significant setup and sterilization operations, while others, for being significantly different, unequivocally lead to setup inefficiencies. Provided that the analysis is restricted to a small set of recipes and considering the difficulty of modeling realistically sequence-dependent setups in such a setting, the recipes are divided into two groups. (1) Recipes that can be easily scheduled without implying cleaning operations (having lower setup costs associated) and (2) recipes that

Table 4.1: Recipe's characteristics

Type	Recipe	Production Volume	Number of SKU's	Setup Costs	Shelf Life
Group 1	Recipe 1.1 (real)	High	High	Low	High
	Recipe 1.2	High	High	Low	Short
	Recipe 1.3	High	High	High	High
	Recipe 1.4	High	High	High	Short
Group 2	Recipe 2.1	High	Low	Low	High
	Recipe 2.2	High	Low	Low	Short
	Recipe 2.3	High	Low	High	High
	Recipe 2.4 (real)	High	Low	High	Short
Group 3	Recipe 3.1	Low	High	Low	High
	Recipe 3.2	Low	High	Low	Short
	Recipe 3.3	Low	High	High	High
	Recipe 3.4	Low	High	High	Short
Group 4	Recipe 4.1 (real)	Low	Low	Low	High
	Recipe 4.2	Low	Low	Low	Short
	Recipe 4.3 (real)	Low	Low	High	High
	Recipe 4.4	Low	Low	High	Short

independently of the production sequence lead to significant setup operations (higher setup costs associated). Only for the second group are the washing and sterilization costs considered in the setup expenditure. Finally, the shelf-life of the products is another differentiating element. The two levels considered are (1) products with high shelf-life and (2) products with a short shelf-life.

Despite Recipe 3.2 and Recipe 3.4 are presented in Table 4.1, producing them would overstep key constraints to which production is subjected. The short shelf life, meaning that products can not be stored long periods before being shipped, and the scarcity of demand orders for some of the recipe's SKUs are the main reasons that inhibit production from complying with the minimum batch size imposed. With this in mind, the aforementioned recipes are excluded from the analysis.

The planning horizon considered is 366 days, and the demand days and quantities coincide with real demand orders of the baseline recipes in a given year.

This approach aims to understand whether characteristics of the production process, such as the setup costs incurred when producing a given recipe, or product-related features such as demand patterns, are relevant to the impact that variations of the MLOR criterion imply. Each recipe intends to mimic a group of recipes with similar characteristics. Each recipe type shares the same demand patterns and the number of SKUs, with setup inefficiencies associated and shelf-life differing between them.

To emulate precisely the production process of the producer, bearing in mind the broad number of recipes produced, a maximum batch size constraint is considered for the high-volume recipes. However, for the low-volume recipes where the production events are less frequent, such constraint is of little importance and dispensable. Thus it is not considered.

Concerning the waste level generated, some assumptions are made. Since waste is a function of the quantities produced in each production day and, more specifically, the reactor used for production, two scenarios are considered and outlined in Table 4.2. Therefore, if a recipe's daily production volume is superior to 4000 kg, reactor A is used, while reactor B is used on the remaining occasions. For recipes that do not oblige significant cleaning operations, waste is independent of the reactor used. Finally, it is worth mentioning that only the last production run of a given reactor generates waste when used to produce the same recipe consecutively.

Table 4.2: Waste generated

Reactor	Capacity (kg)	Waste (kg)
Reactor A	3000	180
Reactor B	750	75

For each of the sixteen recipes considered, the MLOR value is modified, and the outcome is measured. Three alternative scenarios are considered. The baseline scenario entails that products must be delivered with 2⁄3 of their shelf-life, and the remaining two with 1⁄2 and 1⁄3. The results of this experiment are presented in the following section.

For a correct interpretation of the results, it is of the utmost importance to understand that the costs considered in the analysis are the costs that are directly influenced by MLOR, meaning that production costs (a substantial portion of the costs incurred) are not considered in the analysis. Due to confidentiality reasons, the input parameters and results presented in the following section are multiplied by a constant.

4.2 Results

The results obtained for the different recipes analyzed are presented and discussed in this section. The analysis is divided by recipe to understand the importance of product and production process characteristics on the impact that changes on MLOR entail. For each recipe, two indicators are analyzed: costs and generated waste. Results are displayed by recipe type, which means that recipes within each group are analyzed consecutively to understand the dimensions in analysis better. Besides, for similarity purposes, recipes that share the same attributes, differing only in the shelf-life period, are represented and analyzed together.

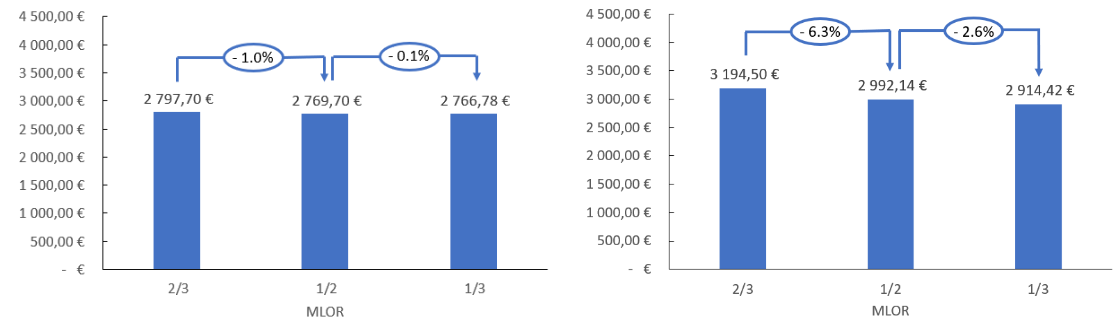
From this point forward, the MLOR value of 2⁄3 will be referred to as the current scenario, 1⁄2 as the moderate scenario, and 1⁄3 as the optimistic scenario.

4.2.1 Group 1 - High Production Volume and High Number of SKUs

4.2.1.1 Recipe 1.1 and Recipe 1.2 - Low Setup Costs

Recipe 1.1 is a real recipe characterized by a long shelf-life, a high number of SKUs, and high annual production volumes that can be easily scheduled without requiring significant setup operations since it is similar to other recipes produced. Recipe 1.2 is an artificial recipe that shares the same characteristics with the real recipe, except for the shelf-life period. Figure 4.1, shows how costs are affected by MLOR for both recipes. Recipe 1.1 displays small cost reductions, with the most significant one being from the current scenario to the moderate scenario (1.0%), while

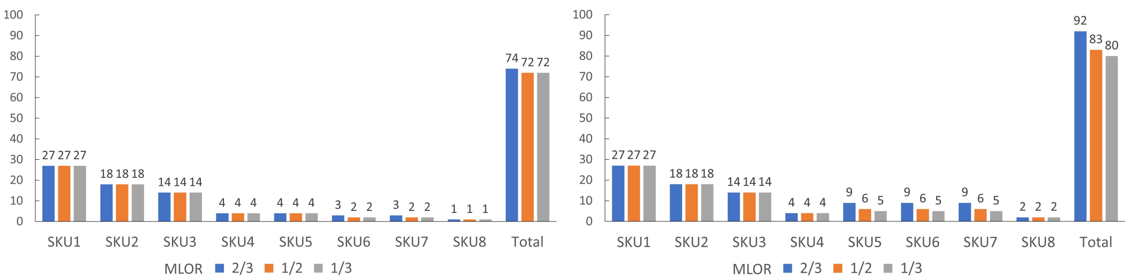
Recipe 1.2 exhibits greater reductions (the most significant also from the current scenario to the moderate scenario, 6.3%).



(a) Recipe 1.1 (b) Recipe 1.2

Figure 4.1: Costs

Since these recipes are easily scheduled without significant cleaning operations, the main portion of costs is associated with setting up the line to produce the different SKUs. Figure 4.2 shows the number of setups performed for each SKU in the filling lines. It is possible to conclude that for the SKUs produced regularly, the number of setups is independent of the MLOR criterion and the shelf-life of the recipe, with the plant capacity being the limiting constraint (maximum batch size). For SKUs infrequently produced, both short-shelf lives and a more rigid MLOR criterion force the number of setups to be increased, with costs following the same trend. Therefore, recipes with short shelf-lives where the MLOR criterion is more favorable allow for a more significant cost reduction, as presented in Figure 4.1.



(a) Recipe 1.1 (b) Recipe 1.2

Figure 4.2: Number of setups for each SKU

Regarding waste, the results are similar for both recipes being displayed in Table 4.3. For Recipe 1.1, the slight decrease in waste generated is motivated by the negligible reduction in the number of production days in the reactor (1,1%) and by the fact that this type of recipe leads to lower wastage levels per production event. For Recipe 1.2, there is an increase in waste generated from the current scenario to the moderate scenario motivated by an increase in the number of production days in the reactor. This increase allows that each SKU is filled less often, allowing for cost reductions.

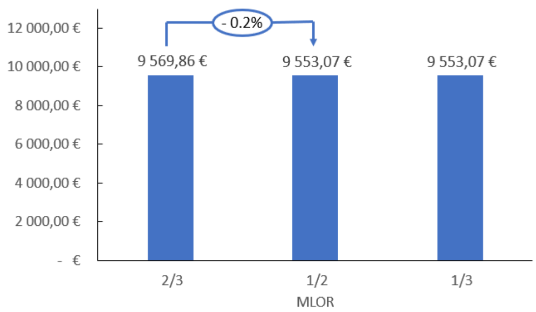
Table 4.3: Waste Generated - Recipe 1 and Recipe 1.1

Recipe	MLOR	Total Production (kg)	Waste Generated (kg)	Percentage of Waste
Recipe 1.1	2/3	751593	2512	0,333 %
	1/2	751593	2475	0,328 %
	1/3	751593	2475	0,328 %
Recipe 1.2	2/3	751593	2512	0.333%
	1/2	751593	2625	0.348%
	1/3	751593	2512	0.333%

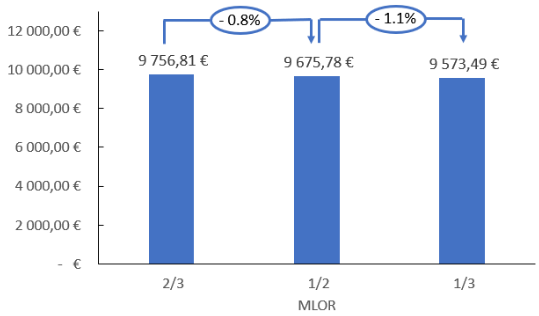
4.2.1.2 Recipe 1.3 and Recipe 1.4 - High Setup Costs

Recipe 1.3 and Recipe 1.4 have many SKUs, high annual production volumes, and usually require sterilization operations when produced. The difference between both recipes concerns their shelf-life period.

The results displayed in Figure 4.3, demonstrate that the impact of MLOR on costs is minimal.



(a) Recipe 1.3



(b) Recipe 1.4

Figure 4.3: Costs

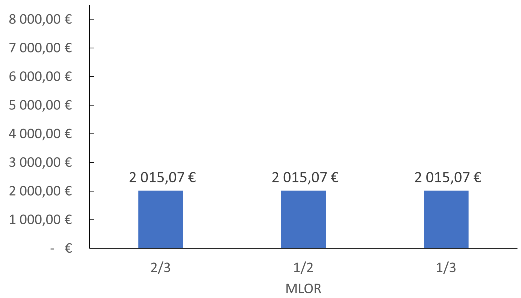
For both recipes, the number of production events in the reactor is equal across the analyzed scenarios due to plant capacity unavailability, forcing more frequent production than needed. Hence, the decrease in costs is motivated by different factors for both recipes. For Recipe 1.3, the main reason for the cost reduction is the more efficient inventory management allowing for lower holding costs, while for Recipe 1.4, the reduction is related to the inferior number of setups performed at the SKU level in the filling lines.

Cost reductions for both recipes are below 2%, denoting the reduced impact MLOR has on recipes with these characteristics.

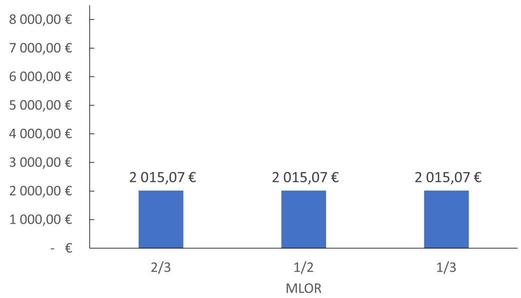
Considering that the number of production events in the reactor is kept constant across scenarios, waste generated displays the same results.

4.2.2 Group 2 - High Production Volume and Low Number of SKUs

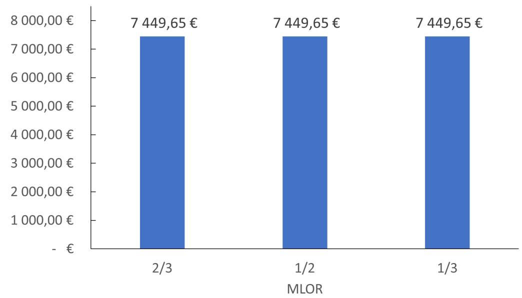
In this section are presented and analyzed the results for the four recipes within Group 2. This exception in terms of analysis approach is justified by the similar results obtained for the recipes considered. All four recipes have only one SKU and are characterized by a high annual production volume. The shelf-life period and the setup costs associated vary between them. Figure 4.4 illustrates the costs impacted by MLOR for each scenario considered.



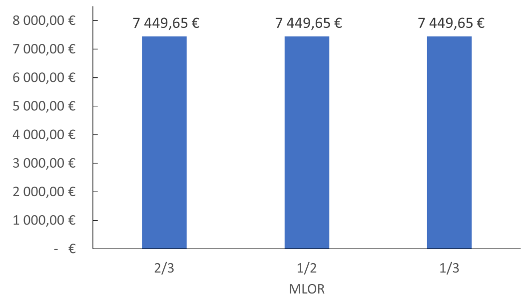
(a) Recipe 2.1



(b) Recipe 2.2



(c) Recipe 2.3



(d) Recipe 2.4

Figure 4.4: Costs

It is possible to conclude that the three analyzed scenarios lead to the same results. This is due to the fact that these recipes are limited by the maximum batch size imposed. Given that they only have one SKU, there are not many arrangements that can be done in production scheduling to decrease the costs incurred when relaxing the MLOR criterion. The difference between the top recipes and the bottom recipes is linked with the setup inefficiencies that arise from producing them. Given that the number of production days is the same, waste levels also remain constant between the different scenarios.

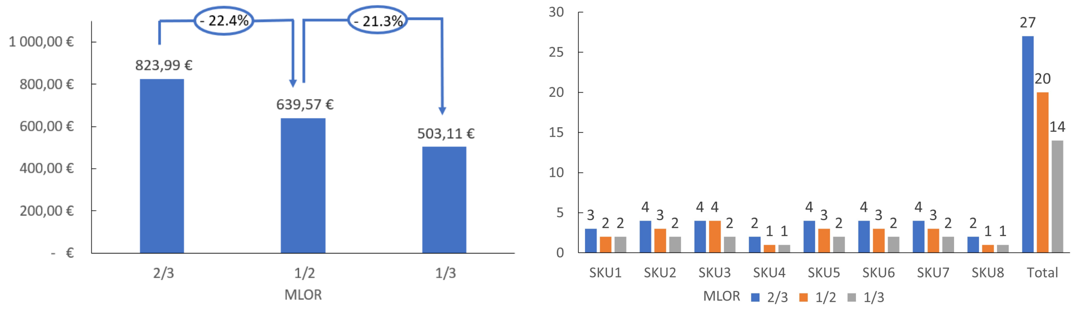
4.2.3 Group 3 - Low Production Volume and High Number of SKUs

4.2.3.1 Recipe 3.1 - Low Setup Costs

Recipe 3.1 typifies recipes with a considerable number of SKUs, high shelf-life, with low annual production volumes that are easily scheduled without requiring significant sterilization operations.

Figure 4.5 displays costs incurred and the number of setups performed per SKU in each scenario analyzed, and Table 4.4 provides the number of production days in the reactor for the current, moderate and optimistic scenario.

The high number of setups performed in the reactor in the first scenario is a consequence of the trade-off between holding and setup costs. Considering that Recipe 3.1 has lower setup costs associated, it is advantageous to produce more often in the current scenario. With a more flexible MLOR criterion, the number of setups can be significantly reduced, making up for the extra holding costs associated. Combined with the number of production days, the decrease in the number of setups performed per SKU is also vital, especially considering that they represent the more substantial portion of the costs incurred in this type of recipe (with low sterilization costs).



(a) Costs (b) Number of setups performed per SKU

Figure 4.5: Recipe 3.1

Table 4.4: Number of production days in the reactor - Recipe 3.1

Recipe	MLOR	Number of Production days in the reactor
Recipe 3.1	⅔	7
	½	4
	⅓	3

Analyzing the results presented in Figure 4.5a, it is observable that the MLOR value adopted has a considerable impact for this recipe, allowing a cost reduction of 22.4% from the current scenario to the moderate scenario, and 38.9% from the current scenario to the optimistic one.

Finally, with Table 4.5, it can be concluded that a lower MLOR value would allow a decrease in waste generated, the most significant from the current to the moderate scenario. (42.9%). Nonetheless, given that recipes with these characteristics generate low relative levels of waste, its effect is diminished when compared with the quantities produced.

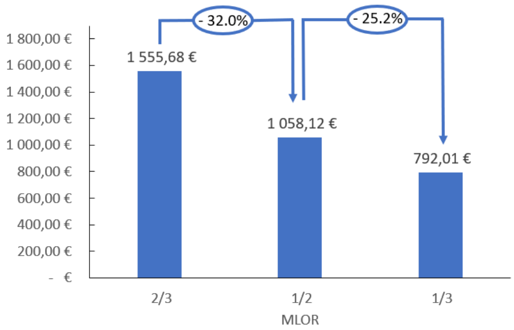
Table 4.5: Waste Generated - Recipe 3.1

Recipe	MLOR	Total Production (kg)	Waste Generated (kg)	Percentage of Waste
Recipe 3.1	⅔	25074	262.5	1.036 %
	½	25074	150	0.595%
	⅓	25074	112.5	0.477 %

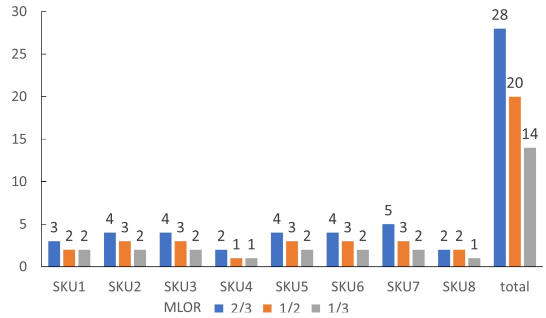
4.2.3.2 Recipe 3.3 - High Setup Costs

Recipe 3.3 intends to model recipes with a significant number of SKUs, high shelf-lives, with low annual production volumes that usually require significant setup operations when produced.

Figure 4.6 illustrates how the different MLOR values impact costs for this recipe and the number of setups performed per SKU in each scenario.



(a) Costs



(b) Number of setups performed per SKU

Figure 4.6: Recipe 3.3

Costs related to the MLOR criterion decrease significantly between scenarios. There is a decrease of 32.0% from the current scenario to the moderate scenario and 49.1% from the current scenario to the optimistic scenario. It is noteworthy that the most notable decrease occurs between the first two scenarios. This decrease is motivated by the number of reactor production runs being reduced by half from the current to the moderate scenario and two-thirds from the current to the optimistic scenario. The reduction in the number of setups performed at the format/SKU level is also important, being illustrated in Figure 4.6b. Considering that low-volume recipes are produced infrequently and that the greater portion of costs for the analysed recipes is imputable to cleaning operations, reducing production days has a considerable impact.

Likewise, the decrease in waste generated is also considerable, with results being illustrated in Table 4.6. The greatest reduction in waste generated is achieved between the current and the moderate scenario (21.62%). From the moderate to the optimistic scenario the reduction amounts to 17.2%.

Table 4.6: Waste Generated - Recipe 3.3

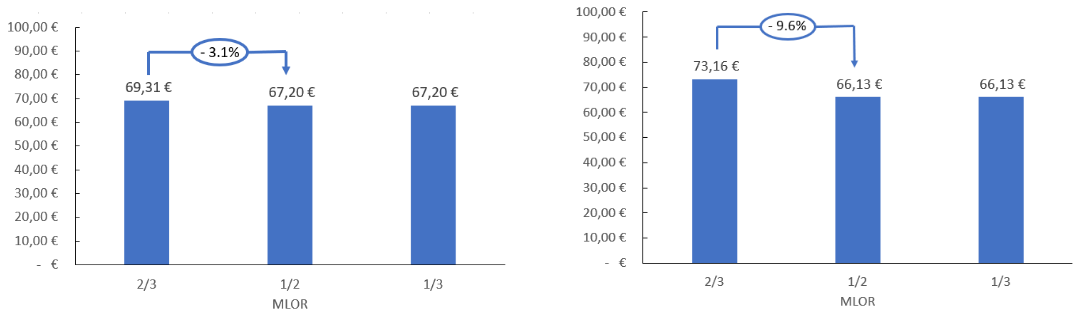
MLOR	Total Production (kg)	Waste Generated (kg)	Percentage of Waste
⅔	25074	555	2.165 %
½	25074	435	1.705 %
⅓	25074	360	1.415 %

Therefore, for recipes with similar characteristics to Recipe 3.3, changes in the MLOR criterion significantly impact waste and costs.

4.2.4 Group 4 - Low Production Volume and Low Number of SKUs

4.2.4.1 Recipe 4.1 and 4.2 - Low Setup Costs

Recipe 4.1 is characterized by a long shelf-life, low annual production volume that can be easily scheduled without requiring significant setup operations since it is similar to other recipes produced. Recipe 4.2 is similar to the previous but has a shorter shelf-life period. Figure 4.7 shows costs incurred in the three MLOR scenarios considered for both recipes.



(a) Recipe 4.1 (b) Recipe 4.2

Figure 4.7: Costs

With Figure 4.7, it is possible to conclude that the effect that variations of the MLOR criterion have on both recipes is similar and reduced. These recipes are produced a few times a year and are similar to other recipes produced, meaning that each production event has lower costs. For that reason, and considering the decrease of production events depicted in Table 4.7, cost reductions are modest. It is important to state that the costs affected by MLOR for these recipes, in absolute terms, are significantly low.

Table 4.7: Number of Production Events - Recipe 4.1 and Recipe 4.2

Recipe	MLOR	Number of Production days in the reactor
Recipe 4.1	2/3	6
	1/2	5
	1/3	5
Recipe 4.2	2/3	6
	1/2	5
	1/3	5

Furthermore, the high number of production events (for a low volume recipe) results from the holding costs that would arise if demand was fulfilled with fewer production runs.

Concerning waste, considering that the number of production events for each scenario is the same for both recipes, the generated waste is also the same. Table 4.8 summarizes the results. The waste generated in the moderate scenario is 17% lower. However, when compared with the quantities produced, its impact is diminished.

Table 4.8: Waste Generated - Recipe 4.1 and Recipe 4.2

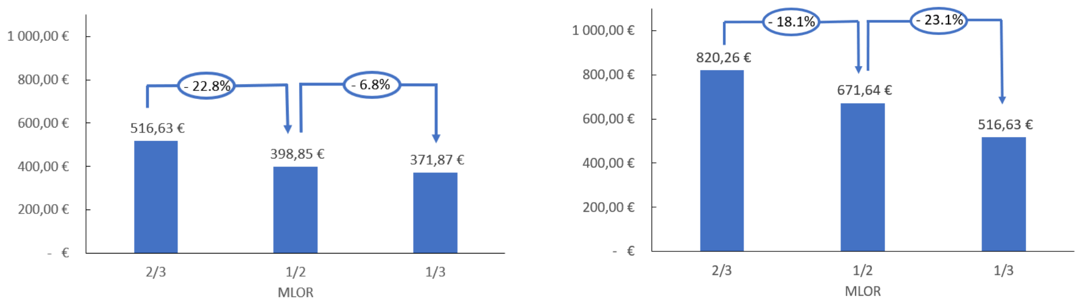
Recipe	MLOR	Total Production (kg)	Waste Generated (kg)	Percentage of Waste
Recipe 4.3	2/3	45337	225	0.49 %
	1/2	45337	187.5	0.41%
	1/3	45337	187.5	0.41 %
Recipe 4.4	2/3	45337	225	0.49%
	1/2	45337	187.5	0.41%
	1/3	45337	187.5	0.41%

4.2.4.2 Recipe 4.3 and 4.4 - High Setup Costs

Recipe 4.3 represents recipes with one SKU characterized by a long shelf-life and low annual production volume that usually requires significant setup operations when produced, given that it is remarkably different from the other recipes produced. Recipe 4.4 has equivalent characteristics, except for the shorter shelf life period. As shown in Figure 4.8 both recipes are significantly affected by MLOR with substantial cost reductions from the current scenario to the moderate and optimistic ones.

For Recipe 4.3, the most emphatic change occurs from the current to the moderate scenario, corresponding to a decrease of 22.8%, which is explained by the lower number of setups performed in the reactor in the latter scenario. Between the last two scenarios, the difference is linked with the capability of fulfilling demand orders closer to their due dates, avoiding unnecessary holding costs.

Regarding Recipe 4.4, cost reductions are similar between scenarios due to the equivalent decrease of production days in the reactor. The higher costs associated when producing Recipe 4.4 occur as a result of the higher number of setups that a lower shelf-life recipe entails. Notwithstanding, it is the higher number of setups that allow wider margins for improvement. From the current to the optimistic scenario, cost reduction amount to 28.0% for Recipe 4.3, while in recipe 4.4 reaches 37%.



(a) Recipe 4.3 (b) Recipe 4.4

Figure 4.8: Costs

Table 4.9, displays the waste generated producing each recipe for the different scenarios considered. For both recipes, waste generated is a substantial portion of what is produced, with the greater savings arising for Recipe 4.4 where there is a reduction of waste of 20% and 40% from the current scenario, to the moderate and optimistic, respectively.

Table 4.9: Waste Generated - Recipe 4.3 and Recipe 4.4

Recipe	MLOR	Total Production (kg)	Waste Generated (kg)	Percentage of Waste
Recipe 4.3	⅔	10210	225	2.16 %
	½	10210	150	1.45%
	⅓	10210	150	1.45 %
Recipe 4.4	⅔	10210	375	3.54%
	½	10210	300	2.85%
	⅓	10210	225	2.16%

With Figure 4.8 and Table 4.9, there is evidence to conclude that both recipes are significantly affected by MLOR in what concerns costs and waste. Even the moderate scenario leads to significant savings for both recipes, making them a critical point of the analysis. Furthermore, these types of recipes represent the majority of recipes of the producer, meaning that the overall impact would also be considerable.

4.3 Discussion

With the results shown above, it is possible to conclude that recipes' characteristics influence the impact that MLOR has on the producer. Table 4.10 and Table 4.11 summarize cost reductions from the current scenario to the moderate and optimistic ones, respectively.

Table 4.10: Cost reduction from the current to the moderate scenario

		High Setup Costs		Low Setup Costs	
		High Shelf-Life	Low Shelf-Life	High Shelf-Life	Low Shelf-Life
High Volume	High Number of SKUs	0.2%	0.8%	1.0%	6.3%
	Low Number of SKUs	0%	0%	0%	0%
Low Volume	High Number of SKUs	32.0%	-	22.4%	-
	Low Number of SKUs	22.8%	18.1%	3.0%	9.6%

Table 4.11: Cost reduction from the current to the optimistic scenario

		High Setup Costs		Low Setup Costs	
		High Shelf-Life	Low Shelf-Life	High Shelf-Life	Low Shelf-Life
High Volume	High Number of SKUs	0.2%	1.9%	1.1%	8.8%
	Low Number of SKUs	0%	0%	0%	0%
Low Volume	High Number of SKUs	49.1%	-	39.0%	-
	Low Number of SKUs	28.0%	37.0%	3.0%	9.6%

Low production volume recipes are a vital point of the analysis, being the ones where the relaxation of MLOR criterion brings more benefits in what concerns costs and waste. Regarding waste, all recipes that share the previous characteristic exhibit significant reductions. The difference is that for the distinct recipes (that commonly oblige considerable cleaning operations), the waste generated is more significant when compared with the produced quantities. Costs are also significantly reduced for these recipes, except Recipe 4.1 and Recipe 4.2, where the magnitude of the impact is diminished. For that, the low number of production events and the low setup costs associated, combined with the holding costs predominance plays a key role.

Contrarily, for the high-volume recipes, the impact of MLOR is negligible. For these recipes, plant capacity forces the producer towards more frequent production events than the ones demanded by MLOR, with the benefits of the relaxation of the criterion coming from small relative decreases in the number of production events and the number of setups performed by SKU. The impact in the generated waste follows the same trend, with insignificant reductions displayed among these recipes.

The shelf-life period is another product characteristic that influences costs and waste. Hence, for recipes with short shelf-lives, where limitations to production planning are superior, more flexible MLOR values allow for increased gains. This means that although shelf life is not a limiting characteristic, it is decisive in the magnitude of the savings. Nonetheless, it is vital to retain that the relaxation of the MLOR criterion for these recipes might be more complicated to reach due to constraints induced downstream of the supply chain.

Additionally, the number of SKUs of the recipe is also significant. For recipes with an increased number of SKUs, the possibility of decreasing the number of setups performed by SKU without reducing the number of production events in the reactor envisages diversified sources for improvement. This impact is more relevant in what concerns costs rather than waste generated. Similar to the shelf-life period, it is not a limiting characteristic yet relevant.

Finally, concerning the setup inefficiencies associated with each recipe, the most significant decreases in costs and waste arise for recipes that usually demand considerable sterilization operations; however, for high volume recipes, the opposite occurs.

It is worth mentioning that the cost-cutting and waste-reduction objectives can be attained simultaneously since both indicators react similarly to a relaxation of the MLOR criterion.

In short, in an attempt for a collaborative effort between players of the supply chain, recipes with low annual production volumes that usually require significant setup operations are the ones of interest considering the impact that MLOR induces. Considering that these recipes represent most recipes produced, the overall impact would also be considerable.

Chapter 5

Conclusion and Future Research

This work represents an introductory study on the impact that the MLOR criterion has on the producer. Even though some works have tackled the MLOR problem, either implicitly or explicitly, this is the first to focus on the producer and production inconveniences arising from this criterion. The MLOR value is currently defined indiscriminately in a setting with immense variability, leaving a significant margin for improvement.

This dissertation addresses a real-life problem presented by a producer of processed food items. Summarily, the MLOR criterion imposes significant constraints on the production process. Thus the company felt that an analysis of the problem ought to be conducted. The main goal was to identify the class of products for which the MLOR criterion impact is more significant. The problem is modeled using a Mixed Integer Linear Programming model adapted from the literature. The model is implemented using Python as a modeling environment and the optimization software Gurobi 9.1.2. Different recipes with specific features are tested, and different MLOR scenarios are analyzed.

With the results obtained, it is possible to validate the premise of this dissertation that the impact of the MLOR criterion is dependent on product and production process features. In most cases, a more flexible MLOR criterion is beneficial. Nevertheless, the magnitude of its impact is substantially distinct. The demand pattern is a crucial characteristic, with the low annual production volume recipes being the ones where the most significant gains are found. Shelf-life, setup inefficiencies, and number of SKUs are other characteristics that influence the impact of the studied criterion. Furthermore, it is noteworthy that significant gains are already attained by the moderate scenario (½ of the shelf-life), which can facilitate and motivate cooperation between parties when agreements regarding MLOR are being made.

Since this is an introductory work on this topic, the main goal was to lay the foundations for subsequent studies on the impact of the MLOR criterion. Although this dissertation gathers valuable insights about how different product characteristics relate to the impact of MLOR, the results obtained can not measure the real overall impact for the producer. For that matter, a more representative set of recipes should be selected, enabling a more precise representation of the real-life problem, the introduction of sequence-dependent setups between recipes, and also a more accurate representation of the capacity constraints considered.

In this dissertation, conclusions are withdrawn based on four characteristics for each recipe. Other product characteristics could be studied. Furthermore, each characteristic can take two levels, yet there is not a clear boundary that defines where the line is drawn. As mentioned before, products with low production volumes are significantly affected by MLOR. Nevertheless, there is not a clear limit that defines what a low production volume recipe is. For the producer, in addition to understanding the type of recipes that are affected by MLOR, it is also important to understand which recipes fall under each type.

Besides, the problem is analyzed in a make-to-order perspective, where the orders are known at the beginning of the planning period. In reality, there is uncertainty associated with this information, and produced quantities are decided in an uncertain setting, often resulting in waste of final product. Thus, incorporating uncertainty would approximate the tackled problem to reality.

Finally, an important constraint of the analyzed problem concerns the maximum batch size considered. For this dissertation, its value was defined based on the expertise of the producer. Notwithstanding, its impact on results is significant, justifying a sensitivity analysis on this parameter.

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