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Tackling food waste in the agri-food supply chain: the impact of a flexible Minimum Life on Receipt (MLOR) rule

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Abstract

Addressing food waste is a critical issue in the Food Supply Chain (FSC). Food waste can arise at every stage of the food supply chain, influenced by the actions of many different players. In distribution (wholesale and retail), quality standards significantly drive food waste at the supplier-retailer interface. A common approach employed by grocery retailers to manage perishable food is the Minimum Life on Receipt (MLOR) rule, which imposes the minimum remaining shelf life a food product must have upon delivery from the producer to the retailer. Typically, this rule is set by retailers and fixed at around 66% of the product's total shelf life. This work proposes an innovative approach, based on a flexible MLOR rule, to manage the interaction between the producer and the retailer in a two-echelon food supply chain of perishable products with a short shelf life, aiming to evaluate the impact of this approach on the profits and waste in the perishable FSC. The proposed interaction is modeled using a Stackelberg game, where the retailer is the leader and the producer is the follower, analyzing a single retailer and producer over three periods for a perishable product with a three-day shelf. The problem is first solved using a centralized optimization model. Subsequently, two decentralized optimization models are developed for comparison: one for the retailer and one for the producer. The focus is on providing the retailer with an economic incentive to implement a flexible MLOR rule, allowing for a lower MLOR value. To deepen the analysis, comparisons are made with the fixed MLOR rule. The models incorporate a discount strategy that allows the adoption of the flexible MLOR rule. This strategy provides a producer-to-retailer discount and a retailer-to-consumer discount for products delivered and sold with a shorter remaining shelf life than required by the fixed MLOR rule. Computational results suggest that the flexible MLOR rule combined with the discount strategy effectively maximizes total supply chain profits. Both the retailer and the producer are expected to benefit from transitioning to the proposed flexible rule. Collaboration emerges as a key factor in optimizing the supply chain, with food surplus reduction appearing more related to the supply chain's power structure than to the MLOR rule itself. This work underscores the importance of considering the retailer’s power when modeling such problems and highlights the effectiveness of discount strategies in optimizing the PFSC. The findings provide innovative insights into the impact of a flexible MLOR rule, offering practical implications for producers and retailers and suggesting directions for future research.

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1. INTRODUCTION

1.1 The problem of food waste

Recently, sustainability has emerged as a vital element in supply chain management. Businesses are placing greater emphasis on Sustainable Supply Chain Management (SSCM) due to its potential to impact the entire value chain and consumer behavior. The food supply chain is a primary focus when tackling environmental sustainability issues. The Sustainable Development Goal (SDG) Target 12.3 aims to halve per-capita global food waste at the retail and consumer levels and to reduce losses along production and supply chains by 2030 (SDG Report, 2023). Additionally, reducing Food Loss and Waste (FLW) supports other crucial SDGs, including sustainable water management (SDG 6), climate action (SDG 13), marine resources (SDG 14), terrestrial ecosystems (SDG 15), and zero hunger (SDG 2) (FAO, 2019).

FLW occurs throughout the food supply chain, from production to consumption. Post-harvest to retail stages alone account for up to 14 percent of globally produced food, valued at $400 billion annually (FAO, 2019). Furthermore, 17 per cent of total global food production is wasted at the retail and consumer levels (UNEP, 2021). 'Food losses' typically occur in the early stages of the supply chain, such as during cultivation, harvesting, post-harvest treatment, and processing. In contrast, 'food waste' refers to losses at the end of the supply chain, during retail and final consumption (FAO, 2019; Gustavsson et al., 2011; Priefer et al., 2016). This thesis, according to Santos et al. (2022), uses the concept of ‘food surplus’ to describe food originally intended for human consumption but diverted from the supply chain for other economic (non-food) uses, typically occurring at the supplier-retailer interface.

The causes of FLW are multifaceted. Meso-level causes include poor organization, coordination, and communication between food supply chain actors, as well as stringent quality standards imposed by retailers. Systemic causes involve inadequacies in institutional, policy, and regulatory frameworks that support actor coordination, enable investments, and promote improved practices along the food supply chain (FAO, 2022).

FLW patterns differ between low and high-income countries. In low-income countries, FLW primarily occurs at early supply chain stages due to inadequate storage facilities, poor infrastructure and transportation, and insufficient packaging. In high-income countries FLW is more prevalent later in the supply chain, driven by quality standards, manufacturing scraps, poor environmental conditions during display, and a lack of communication, coordination, and consumer awareness (Gustavsson et al., 2011b).

The food supply chain (FSC) is unique due to continuous changes in the quality of food products until final consumption. Among FSCs, the perishable food supply chain (PFSC) is particularly critical from a management and sustainability perspective (Paam et al., 2016). Perishable foods, such as fresh produce, meat, seafood, bakery, and cooked food, have limited shelf lives, making them prone to significant FLW. Globally, 40–50% of all root crops, fruits, and vegetables are wasted (Gustavsson et al., 2011b), leading to substantial wastage of resources used in production, transportation, and marketing (Kumar et al., 2020). Effective revenue management for perishable foods is vital for retailers due to the highly competitive market environment (Chen et al., 2019). Consequently, efficient PFSC management is crucial for reducing operational costs and FLW throughout the supply chain (Paam et al., 2016).

Measures such as optimizing inventory and ordering, improving storage and transport technology, and designing dynamic pricing policies for suppliers and retailers have been employed to reduce FLW in the FSC. However, conflicting incentives between suppliers and retailers lead to uncoordinated behaviors and low collaboration, undermining FLW reduction efforts (Li et al., 2021). Food waste at the supplier-retailer interface has only recently been explored. Retailer waste is easily accounted for, whereas waste from rejected or returned products to suppliers is less noticeable (Weber, 2022). This waste stream, identified in this work as food surplus, is driven primarily by contracts at the supplier-retailer interface (Canali et al., 2014). Contracts enforcing stringent delivery conditions and unsold product policies can lead to waste, as powerful food chain operators (downstream) tend to shift the risk and cost of unsold products onto weaker operators (upstream) (Ghosh & Eriksson, 2019a). Recently, the power dynamics in the FSC have shifted, with retailers gaining dominance, thereby influencing cooperation and contractual policies significantly (Maglaras et al., 2015).

A contractual policy widely used by powerful retailers is the Minimum Life on Receipt (MLOR). This thesis addresses FLW at the supplier-retailer interface, focusing on the potential of implementing a collaborative MLOR policy and pricing strategy. By doing so, it aims to enhance both economic and environmental performance across the supply chain. The MLOR rule is presented in Section 1.2.

1.2 The Minimum Life on Receipt

The Minimum Life on Receipt refers to the minimum remaining shelf life that a product must have upon its receipt into a retailer’s inventory. Widely employed in perishable food supply chains (PFSCs), this contractual policy between producers and retailers aims to manage inventory effectively and ensure products are sold before they expire. In practical terms, retailers typically set this as a fixed requirement, in particular, products must have at least 66% of their remaining shelf life to comply with MLOR specifications (Santos et al., 2022). Products arriving with less than the stipulated remaining life under MLOR are often rejected and removed from the food supply chain, categorized as either food waste or potentially redirected as food surplus for secondary markets. Figure 1 illustrates the fixed nature of the MLOR rule.

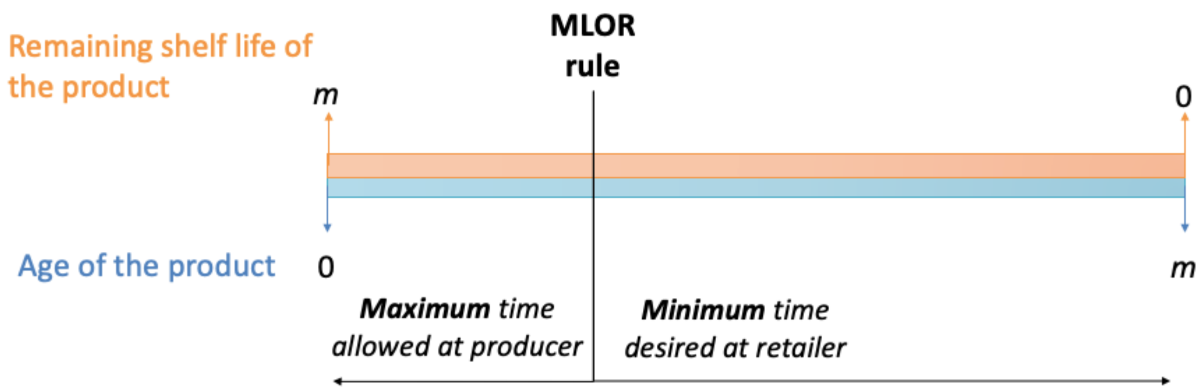

Figure 1. Fixed MLOR rule

While MLOR allows retailers to maintain inventory control and meet consumer expectations for product variety and freshness, it imposes significant constraints on producers' production planning flexibility. In scenarios of uncertain retailer orders, producers face high risks of either failing to meet orders or dealing with excess waste. A study from the Waste and Resources Action Programme (WRAP, 2015) suggested increasing the MLOR as a measure to reduce household food waste. However, household waste constitutes only a fraction of total food waste, and a strict MLOR requirement may result in substantial product rejections by retailers, leading to significant upstream waste at the producer level. Mandating fresher products through stringent operational constraints on producers alone does not efficiently address food waste, as substantial amounts are already lost before products reach consumer refrigerators (Karadeniz, 2014). Therefore, the goal of reducing food waste must encompass the entire supply chain.

1.3 Motivation for the thesis

The rigid implementation of the MLOR rule in decentralized decision-making often leads to inefficiencies and increased waste. Surprisingly, literature addressing the impact of the existing MLOR rule on food loss and waste, and proposing alternative approaches, remains scarce. Santos et al. (2022) introduce flexible MLOR rules that vary based on shelf-life and operational constraints of producers. Their research demonstrates that a modest 12% relaxation in MLOR requirements results in minimal (up to 1%) reduction in average freshness, yet significantly reduces waste at the producer level and enhances overall supply chain profitability. Meanwhile, Mohamadi et al. (2023) explore collaborative opportunities between retailers and producers in setting MLOR values. They find that lower MLOR levels nearly eliminate expected waste at the manufacturer's end, with negligible increases in retailer waste, enabling producers to lower wholesale prices. Building on these insights, this thesis aims to delve deeper into the implementation of flexible MLOR rules.

This study explores potential collaboration points along the supply chain when MLOR rules are not fixed: (1) producers can leverage reduced operational costs to offer discounted bulk purchases to retailers who accept deliveries containing compliant and non-compliant items, (2) retailers can capitalize on increased profits from lower purchasing costs to offer consumer discounts on older items, thereby reducing waste at the producer level without increasing retailer waste.

While this analysis does not consider household waste, it is important to note that a significant reduction in MLOR from 66% to 33% does not equate to a proportional decrease in freshness. Moreover, flexible MLOR rules provide producers greater flexibility in production planning, potentially reducing the volume of older products delivered. Consumer awareness plays a crucial role; they are likely to purchase discounted items only if they intend to consume them promptly.

Ultimately, this strategy aims to increase retailer profitability and provide managerial insights to the dominant actors in the supply chain to transition towards flexible MLOR rules.

The remainder of this thesis is structured as follows. Section 2 provides a literature review of relevant works to contextualize the problem and highlight the contributions of this study. Section 3 outlines the methodology, establishing the Stackelberg game and describing the mathematical models formulated. In Section 4, computational results are presented and discussed to compare various scenarios. Finally, Section 5 concludes with the key insights of this work, discusses its limitations, and suggests directions for future research.

2. LITERATURE REVIEW

In this section two separate research streams are analyzed: the application of game theory to model and solve supply chain problems, and the policies governing interactions between producers and retailers of perishable products. It provides an overview of key research in each area and situates this study at their intersection.

2.1 Game Theory in Supply Chain Analysis

Game theory (GT) has been a widely used methodology in the analysis of supply chains in which the decisions of multiple agents have conflicting objectives. The use of game theory in the design or redesign of supply chain logistics strategies allows these chains to be economically optimized by evaluating and outlining decision paths that lead to greater profitability, cost reduction, or improved resource management.

Cachon & Netessine (2006) summarize in a review the various game theory methods and techniques used in literature to study the supply chain, demonstrating its great potential in addressing Supply Chain Management (SCM) problems. They distinguish two branches of game theoretic models, depending on the nature of the interaction among the players: noncooperative game theory (NCGT) and cooperative game theory (CGT). CGT models how agents cooperate to create and capture value, without specifying the actions each player will take. NCGT focuses on each specific action of the agents and maximizes their utility, based on a detailed description of the moves and information available to each agent (Chatain, 2014). NCGT has long enjoyed more attention than cooperative GT in the economics literature. Papers employing cooperative GT to study SCM have been scarce, although their popularity is increasing (Cachon & Netessine, 2006). Leng & Parlar (2005) analyzed 139 articles concerning the application of game theory to SCM and classified them according to their cooperative or noncooperative nature. The results show that 65% of the papers belong to the noncooperative branch, only 24% to the cooperative branch, and 11% to both.

Non-cooperative game theory can be applied in static or dynamic settings. In a game, the potential actions available to players are called strategies. Each player's set of strategies includes all possible strategies available to them. When players in a game choose their strategies, specific payoffs are obtained as outcomes for all parties involved. Static games take place over a single period, in which players simultaneously choose their strategies and commit to them in subsequent periods. Dynamic games, on the other hand, are extended over multiple periods, with players taking decisions sequentially over time. In the static setting, Nash equilibrium is the most widely used approach, while in the dynamic context, the Stackelberg game is the most popular (Cachon & Netessine, 2006). The Stackelberg game, proposed by Von Stackelberg, is also called leader-follower game because of the presence of the Stackelberg leader, who first chooses the strategy to be adopted to maximize its payoff assuming the follower acts rationally, and the Stackelberg follower(s), who reacts to optimize its objective function given the leader's actions. In some SCM problems, this solution concept is more realistic than the Nash equilibrium, because often one member of the supply chain plays the role of a leader by first announcing its strategy to the other member(s) (Leng & Parlar, 2005).

Agi et al. (2021) provide a detailed review of game-theory models used in Green Supply Chain Management (GSCM). GSCM involves integrating sustainable environmental choices into the SCM (Srivastava, 2007). The literature reviewed consists of 108 papers and is found to be dominated by noncooperative sequential game models. Specifically, 80% of the articles use the Stackelberg model. Most of the literature reviewed (96 articles) focuses on two-level SCs. Analysis of the power structure of these supply chains showed that 59% of the papers assume the manufacturer is the leader, while 20% assume it is the retailer. However, in recent years, the market structure has shown a shift of the command power from producers to retailers (Z. Huang & Li, 2001) and it is therefore likely that a reversal of the trend will occur in future studies. Additional relevant findings from the literature review concern competition, consumer demand characteristics, and the objective functions of players in game theory models. Among the 108 articles examined, only 43 include competition into the model, while the remaining articles consider monopolistic markets where a single SC entity produces and sells a single product. Consumer demand functions encompass both deterministic and stochastic models, with 72% of the papers utilizing deterministic models. Regarding objective functions of models applied to Green Supply Chain Management, most studies focus on profit-based payoff functions for the entire supply chain and for its individual members. Consequently, the environmental impact or greenness level results from the behavior of SC members who seek to maximize benefits or minimize costs (Agi et al., 2021).

In the next paragraphs we will review the literature related to applications of game theory to address pricing problems in supply chains and perishability/waste problems in the food supply chain.

2.1.1 Game Theory applications for discount

Coordination plays a crucial role in improving supply chain performance. Coordinating a supply chain is equivalent to solving a problem of competition and cooperation. Game theory stands out as a very effective approach to address these problems, assuming that supply chain participants are involved in both cooperative and noncooperative games (Kazemi & Saeedmohammadi, 2016). Conflicting objectives can be addressed through coordination contracts specifying the parameters (such as quantity, price, time, and quality) within which the buyer places orders and the supplier fulfills them. Among these, discount contracts are widely used in the literature as a cooperative mechanism to increase the profit of SC members and the entire chain (Nouri et al., 2021). This is proved by the review of Agi et al. (2021) in which the topic of optimal pricing is addressed by as many as 79 out of 108 analyzed articles, and specifically 70 focus on determining the optimal consumer price and the optimal product price at the interface between members of the supply chain.

This section explores the existing literature on the application of game theory for modeling and solving supply chain problems using the discount contract as a coordination mechanism. From here on, the term supplier is interchangeable with seller, just as buyer is interchangeable with retailer.

This work focus on quantity discount, since it is the most common discount used by the supplier to induce the buyer to accept the coordination. A quantity discount is a pricing strategy where the seller offers a lower unit price to buyers who purchase a larger quantity of a product. The discount encourages buyers to order more, benefiting both parties: the seller can increase sales volume and reduce inventory costs, while the buyer saves money on each unit purchased. From the viewpoint of operation, the discount mechanism impacts to reduce ordering and inventory costs (Li, Liu, 2006). The effectiveness of quantity discount relies on two key factors: the sensitivity of consumer demand to price changes and the relationship between operating costs and quantity ordered.

One of the earliest works in this field is developed by Monahan (1984), who propose a quantity discounting model between supplier and retailer to determine the optimal levels of order size and corresponding price discount to maximize the supplier's incremental profit. The paper considers the scenario in which manufacturer and retailer are involved in a Stackelberg game.

Chiang et al. (1994) explore the discounting problem in both competitive and cooperative settings. The noncooperative game is solved with a Stackelberg equilibrium, considering the seller as the leader, while in the cooperative game they use the Pareto optimal criterion to identify optimal strategies. The results show that quantity discounts serve as a mechanism to coordinate channel members.

Parlar & Wang (1994) study the discounting decisions for a supplier with a homogeneous group of buyers, under the assumption that discounting attracts greater demand from buyers. The solution is found with the Stackelberg equilibrium, considering the supplier as the leader. It is proved that both parties can gain significantly from the quantity discount and that this mechanism can be very efficient in maximizing the gain of the entire supply chain.

Q. Wang (2001) develops a noncooperative Stackelberg game to coordinate a two-echelon distribution system consisting of one seller and multiple buyers. Again, the leader is the seller, and the coordination mechanism is the quantity discounting. The benefits of coordination on the seller's profit are shown.

Su & Shi (2002) developed a game model involving quantity discounts and buyback decisions. The scenario is modeled by a two-stage game solved first by a Nash-Cournot equilibrium and then by finding the Pareto optimum. The results show that the returns policy can be viewed as the mirror image of a quantity discount strategy since both have the effect of increasing the order quantity.

Esmaeili et al. (2009) used cooperative and noncooperative game theory to evaluate the impact of cooperation on selling price, marketing expenditure and lot size. The noncooperative game is considered from the seller-Stackelberg and from the buyer-Stackelberg perspectives. The Pareto efficient solutions are obtained by assuming the seller and buyer negotiate an agreement on the price charged by the seller to the buyer. It is found that, using this negotiation, the selling price charged by the buyer to the consumer, marketing expenditure and lot size are lower than in a non-cooperative scenario.

Karray & Surti (2016) assessed the effects of quantity discounts and cooperative advertising as coordination mechanisms between a manufacturer and a retailer. They solve four Stackelberg games: in the first, neither mechanism is implemented; in the second, only cooperative advertising is adopted; in the third, only quantity discounting; and in the fourth, both. The manufacturer is assumed to be the Stackelberg leader. From the comparison between the two mechanisms, quantity discounting appears to be the most profitable when used alone.

Kazemi & Saeedmohammadi (2016) focus on coordinating two-tier supply chains, comprising a manufacturer and a retailer, using cooperative advertising together with pricing strategies. Specifically, the manufacturer will provide a price discount to the retailer, and demand will be influenced by both pricing and advertising. The producer-Stackelberg game and the retailer-Stackelberg game models are examined. The results of the second model, relevant to our work, show that when the retailer is the leader, it sets a low retail price to gain a higher marginal profit from increased demand, thereby convincing the manufacturer to set a lower wholesale price. Therefore, this paper confirms that the manufacturer-to-retailer discount and the retailer-to-consumer discount have a positive effect on increasing total profitability when demand is price-sensitive.

The literature shows that many studies have addressed the problem of supply chain coordination through the discount mechanism using game theory for its resolution. The most used discount mechanism is related to the quantity ordered. Existing studies demonstrate the effectiveness of discount mechanisms for supply chain coordination and the appropriateness of game theory for modeling this type of problem. However, there are no studies that consider other factors, such as quality or perishability. Game theory applications addressing perishability issues are reviewed in section 2.1.2. A summary of the abovementioned literature is provided in Table 1.

Reference	Methodology	Discount type	Supply chain type
Chiang et al. (1994)	• Supplier-Stackelberg • Pareto optimality	• Supplier-to-retailer quantity	• Two-level
Esmaeili et al. (2009)	• Supplier-Stackelberg • Retailer-Stackelberg • Pareto optimality	• Supplier-to-retailer	• Two-level
Karray & Surti (2016)	• Supplier-Stackelberg	• Supplier-to-retailer quantity	• Two-level
Kazemi & Saeedmohammadi (2016)	• Supplier-Stackelberg • Retailer-Stackelberg	• Supplier-to-retailer • Retailer-to-consumer	• Two-level
Monahan (1984)	• Supplier-Stackelberg	• Supplier-to-retailer quantity	• Two-level
Parlar & Wang (1994)	• Supplier-Stackelberg	• Supplier-to-retailer quantity	• Two-level (multiple retailers)
Su & Shi (2002)	• Nash-Cournot • Pareto optimality	• Supplier-to-retailer quantity discount	• Two-level
Q. Wang (2001)	• Supplier-Stackelberg	• Supplier-to-retailer quantity	• Two-level (multiple retailers)
This work	• Supplier-Stackelberg	• Supplier-to-retailer • Retailer-to-consumer	• Two-level

Table 1. Summary of existing literature on of game theory applications to pricing decisions

2.1.2 Game theory application for perishability

While numerous studies have explored the dynamic pricing problem for deteriorating items, there is a scarcity of literature that employs game theory to model and solve this issue. This section reviews the literature most relevant to this study, focusing on works that apply game theory to shelf-life management of perishable foods.

C. Wang & Chen (2017) consider a fresh produce supply chain that consists of a supplier who is the Stackelberg leader and a retailer who is the follower. They found that the SCs with wholesale price and portfolio contracts can be coordinated to achieve a Pareto improvement for both parties and that the supplier cannot realize its optimal pricing strategy within this coordinated framework. However, in this model the product perishability is not involved in pricing decisions.

H. Huang et al. (2018) establish a Stackelberg game model for a three-level food supply chain involving a retailer, a vendor, and a supplier, with product deterioration. In the decentralized SC, upstream firms act as leaders while downstream firms act as followers. They discover that vertical cooperation improves overall profits and reduce carbon emissions. Additionally, they compare two integration strategies: forward integration, where food companies integrate with downstream sellers, and backward integration, which involves collaboration between upstream producers and vendors. Forward integration is found to be more effective than backward integration.

In the analysis by Chen et al. (2019), the optimal pricing strategy for perishable foods is examined from the perspective of a two-echelon supply chain consisting of a supplier and a retailer. They employ a game theory approach to derive and compare the equilibrium points of a single pricing strategy and a two-stage pricing strategy. The power structure follows a vertical Nash equilibrium, indicating a balanced power relationship between the supplier and retailer. Customer demand is influenced by both retail price and product quality, consistent with previous research by X. Wang & Li (2012). Key insights arising from the analysis are the following: (1) employing a two-stage pricing strategy yields higher profits for the retailer compared to a single pricing strategy under specific conditions (when the markdown cost is below the critical threshold of the retailer's markdown cost); (2) with the two-step pricing strategy, the retailer sets a higher retail price in the first step, exceeding the optimal retail price of the single price strategy, and then reduces the price in the second step; (3) the supplier sets a lower wholesale price when employing the two-stage pricing strategy; (4) the supplier is always better-off with the two-pricing strategy as this captures a larger share of customer demand, and (5) in scenarios where the retailer is worse off but overall supply chain performance improves, coordination within the perishable food supply chain can be achieved through profit-sharing contracts.

Hendalianpour (2020) develops a game-theoretic model for the decision made on pricing and lot-sizing by retailers of perishable goods. Only the retailer and customers are involved in the game. Demand depends on base price, sales price, product freshness and inventory amount. The main findings of the study can be summarized as follows: (1) pricing strategies play a crucial role in the success of a grocery store; (2) consumer purchase decisions are notably influenced by the reference price; (3) increasing the quantity of inventory displayed encourages customers to purchase more items, and (4) for customers, product freshness, as denoted by the expiry date, is the most important criterion. Consequently, they determine whether to make a purchase by comparing the product's price with its freshness.

Li et al. (2021) investigate a collaborative effort strategy to reduce food loss and waste (FLW) in a two-tier FSC, comprising a single supplier and a single retailer, using quantum game theory. They conclude that aligning the interests of the supplier and retailer through a quantum contract incentivizes both parties to collaborate effectively to reduce FLW.

Mamoudan et al. (2022) present a game theory model for a two-echelon food perishable supply-chain with a supplier and many retailers. The model considers the brand value of manufacturers, the price of products, perishability, and advertising, and is developed under two scenarios: with discount and without discount. The supplier acts as the leader, while retailers are the followers. The results show that the food supply chain is optimized with a quantity discount contract and that cooperation generates higher profit for both the supplier and the retailers compared to independent procurement. Furthermore, from the sensitivity analysis on the deterioration rate, it is evident that as this rate increases, the supplier's selling price decreases.

Existing literature shows that game theory is a well-established methodology to address perishability issues and that discounts are often employed to tackle this problem. However, there are no studies that model the interaction as a Retailer-Stackelberg game. A summary of the abovementioned literature is provided in Table 2. This work aims to contribute to this stream of investigation by considering pricing decisions, perishability, and game theory in a two-tiered food supply chain dominated by the retailer.

Reference	Methodology	Discount type	Perishability	Supply chain type
Chen et al. (2019)	• Nash	• Supplier-to-retailer • Retailer-to-consumer	• Perishable food	• Two-level
C. Wang & Chen (2017)	• Supplier-Stackelberg	• Supplier-to-retailer	• Perishable food	• Two-level
Hendalianpour (2020)	• Optimality	• Retailer-to-consumer	• Perishable food	• One-level (retailer)
H. Huang et al. (2018)	• Supplier-Stackelberg	• No discount	• Perishable food	• Three-level
Li et al. (2021)	• Quantum game	• Quantum contract	• Perishable food	• Two-level
Mamoudan et al. 2022)	• Supplier-Stackelberg	• Supplier-to-retailer quantity	• Perishable food	• Two-level (multiple retailers)
This work	• Retailer-Stackelberg	• Supplier-to-retailer • Retailer-to-consumer	• Perishable food	• Two-level

Table 2. Summary of existing literature on of game theory applications to food perishability

2.2 Contractual policies in the agri-food supply chain

Policy measures in the perishable food supply chain between suppliers and retailers can be a low-cost option for minimizing waste. Numerous quantitative models have been developed to assess the impact of various agreements on supply chain waste and to propose new strategies. However, there is very limited qualitative literature on the subject. The existing policies for managing perishables remain largely unexplored. Due to mostly private nature of these arrangements and the lack of governmental regulation, information is scarce and limited to very specific cases.

Fulponi (2006) interviewed quality and safety managers of major Organization for Economic Co-operation and Development (OECD) retailers and conducted a brief survey of retailers' purchasing practices. It was found that companies apply specific criteria for taste, smell, texture, appearance, and product integrity, considering quality standard almost as relevant to their reputation as food safety. Suppliers are required to meet these standards, otherwise they are excluded from the market and potentially forced to exit the sector. This is especially critical for small and medium suppliers, who often struggle to meet these stringent conditions. Moreover, several firms have developed high-quality product lines that adhere to much higher and more stringent private standards than the industry average, confirming the increasing use of private standards.

Canali et al. (2014) provided a detailed qualitative analysis of food waste drivers in the FSC. They found that contractual relations, where parties with the highest bargaining power (mostly retailers) shift the costs of waste disposal for unsold products onto weaker counterparts, are significant contributors to food waste. Among potential future strategies for waste reduction, they suggest discounting products close to their expiry date or damaged products, either by the supplier or retailer. While these approaches might create a perception of lower quality among consumers, the authors claim that encouraging closer relationships between suppliers, retailers and consumers can raise public awareness about the waste problem and the misleading relationship between food classification and quality, helping to reduce food waste.

Göbel et al. (2015) studied the causes and effects of waste in the German food supply chain. For vegetables, retailer quality standards and product specifications were identified as the main causes of food waste. Dairy products are often rejected by retailers due to their short residual shelf-life. Overall, food waste at the supplier-retailer interface is mainly attributed to differences in quality requirements, product specifications, grading, and marketing standards. Retailers set their own regulations on acceptable quality, often using norms that are not mandatory for the protection of human life, which leads to unnecessary food waste when products fail to meet these standards.

Maglaras et al. (2015) examined the most significant practices applied in the dyadic, supplier-retailer relationships in the Greek food chain, which has been affected by the arrival of many international retailers such as Carrefour, Delhaize Le Lion, and Lidl. This has led to increased market concentration, with the top five retailers accounting for 56% of the grocery market, and the resulting shift in power in favor of the retailer. Among the practices identified, those relevant to this thesis are: product returns, buy back unsold products outside the agreement, obscure terms of agreement, and promotional price that are offered by a supplier and does not appear in the final price.

Australia represents another case of a highly concentrated food retail sector, where Coles and Woolworths control over 70% of the market share. Devin & Richards (2018) discuss how these supermarkets use their structural power to meet corporate social responsibility (CSR) goals, effectively shifting the problem of food waste elsewhere in the SC. Interviews with food retailers, food rescue organizations, and industry bodies representing primary producers revealed supermarket specifications are a key cause of food waste in the supply chain. The study argues that retailers strategically reduce the cost associated with food waste while maintaining their public reputation by implementing waste targets, such as zero-waste policies, in stores. The authors suggest that genuine engagement, including relaxing standards for fruits and vegetables, would be more effective in reducing food waste.

Several studies tackled the issue of food waste resulting from the strong power of retailers in Swedish supply chains. Eriksson et al. (2012), examined fruit and vegetable waste in six retail stores in the Stockholm-Uppsala region, all owned by the Willys chain of stores. It differentiated between waste caused by retailer rejection due to non-compliance with quality standards (pre-store waste) and waste from unsold products in the store (in-store waste). The study found that pre-store waste accounts for 70% of total fruit and vegetable waste, while in-store waste accounts for 30%. This indicates that most waste results from the rejection of deliveries deemed non-compliant, despite both suppliers and retailers claiming to have high quality standards. This highlights a disagreement over which products are considered qualitatively edible. Eriksson et al. (2017) focused on bread, fruits and vegetables, as they are highly perishable products with short shelf-life. Data on fruits and vegetables waste are collected from Willys and ICA retailers. Consistent with Göbel et al. (2015) , it was found that return policies for fresh fruit and vegetables are internal supermarket policies, as there are no detailed requirements defined by both parties. The procedure for reclamations requires that when products do not meet quality standards they are recorded as pre-store waste. However, not all non-compliant items are always rejected; for instance, a store once ordered lettuce with 5-day shelf-life but received lettuce with only 2 days remaining. The supplier offered a 35% discount on the delivery and the retailer decided to keep the lettuce, illustrating that economic bargaining can reduce rejections. Information on bread rejection is obtained from Saltå Kvarn, a medium-sized Swedish grain supplier and bread producer, and from interviews with major bread suppliers and retailers in Sweden. In this category, the return policy is a Take Back Agreement (TBA), which allows retailers to give back unsold bread and pay only for the amount sold, externalizing the risk and cost of the generated food waste (Brancoli et al., 2019). This is an extreme yet common practice. The findings indicate that rejections and TBAs drive pre-store food waste, as retailers, bearing less direct cost of waste, have lower incentives to prevent it. The study suggests designing economic incentives within the food supply chain to reduce waste generation. Finally, in Ghosh & Eriksson (2019) the TBA's implications are explored in depth, using data from the manufacturer Saltå Kvarn. This producer decided to share sensitive information after exiting the market. Between 2011 and 2015, Saltå Kvarn experienced a 30% return rate on its total production volume, resulting in such significant revenue losses that it decided to cease operations. Extending these findings to other small and medium-sized producers, the study suggests that TBAs can create a barrier to the entry of new producers, as only larger bread companies are able to negotiate better contracts. The work argues that TBAs act as a tool of coercive power, and proving their effects is challenging due to their confidential, bilateral nature.

The literature clearly shows that contract policies significantly impact food waste at the supplier-retailer interface, favoring retailers by allowing them to reduce in-store waste and costs while enhancing their CSR efforts. However, the disadvantages for suppliers are evident. These practices include rejecting products that do not meet the quality standards, often at the retailer's discretion, and, in the Swedish case of bread, extreme agreements like the TBA. The TBA requires producers to accept unpaid returns of unsold products and bear the disposal cost. Although these practices are not directly related to the short life of perishable food products, they highlight the existence of strict regulations, such as the Minimum Life On Receipt (MLOR) rule, which will be discussed in Section 2.2.1.

2.2.1 Fixed and flexible MLOR rule

The point at which a product is received by the retailer is crucial for monitoring its remaining shelf-life. To ensure that products are delivered with sufficient life for consumers, retailers accept only those products that meet a pre-agreed minimum remaining life. This measure of performance, known as Minimum Life On Receipt (MOLR), is an age-dependent criterion applied to products with a fixed life, and is set by the retailer. MLOR specifies the minimum percentage of a product's shelf life that must remain when the product is received by the retailer. Although this topic is part of a broader discussion on supply chain management and regulations, there is limited literature addressing this specific rule.

According to WRAP (2015) retailers require that 75% of the remaining shelf-life be available for long-life product (those with a shelf-life greater than 7 days) upon delivery. However, for short shelf-life products, daily negotiation with suppliers occurs. Retailers may accept products with a remaining life below the standards for short-life products, which could increase waste in stores and in households. Alternatively, they can reject the delivery, which could also give rise to waste at the suppliers' warehouse.

Akkas & Honhon (2021) analyzed shipment policies regarding the quantity and age composition of inventory shipped from a producer to a retailer, and their impact on profits and waste. They focus on consumer-packaged goods (CPG) with a MLOR rule between 5 to 6 weeks. Their findings indicate that the Ship-Oldest-First (SOF) policy always minimizes total waste, but it does not maximize profits. Additionally, SOF has the disadvantage of increasing expiration rates at retail and waste in households.

Santos et al. (2022) explored the opportunity to optimize the MLOR rule as decision variable, rather than treating it as a fixed rule. They develop a single-echelon model for the producer and a two-echelon centralized model for the integrated retailer-producer system. The models define flexible MLOR rules differentiated by shelf-life and production lot size, and compare their effects with a fixed MLOR scenario. Results show that flexible MLOR rules reduce total waste and increase profit in both models. The impact on the average freshness of products from relaxing the MLOR rule by 12% is minimal, at most 1%.

Mohamadi et al. (2023) consider the MLOR rule as a decision variable in a Stackelberg game between a retailer and a supplier. In this setup, the retailer is the leader and can offer an agreement that requires a lower MLOR to the supplier. The supplier, as the follower, accepts the agreement if it is profitable. They investigate the effect of the MLOR agreement on supply chain waste and profits. Results show that reducing the MLOR by one period (day) shelf life nearly eliminates the long-run expected waste for the supplier, while the increase in waste at the retailer is negligible. Additionally, the wholesale price from the supplier decreases when he is not restricted to deliver the freshest products, thereby increasing the retailer's profit.

Research on the MLOR rule is in its early stages and remains limited. Current studies highlight the potential of a lower MLOR value to reduce waste at the supplier-retailer interface and enhance supply chain profitability, while its effects on waste generated at the retailer level and in households have not yet been explored. Lowering the MLOR value shows minimal impact on product freshness while boosting profits and reducing waste, and it enables producers to decrease wholesale prices by cutting operational costs. However, no studies have proposed an incentive for retailers to shift from a fixed to a flexible MLOR rule. This work advances the literature by investigating the effects of a flexible MLOR rule and presenting a model advantageous to both suppliers and retailers. The model not only evaluates the economic benefits of relaxing the MLOR value but also introduces a novel discount system from the manufacturer to the retailer and from the retailer to the consumer, fostering a reduction in waste.

Reference	**Methodology**	**MLOR rule**	**Discount type**	**Demand**
Mohamadi et al. (2023)	• Retailer-Stackelberg • Decentralized problem	• The wholesale price is a decision variable	• Supplier-to-retailer	• Stochastic

Santos et al. (2022)	• Centralized problem	• MLOR value is a decision variable	• No discount	• Deterministic + rolling horizon
This work	• Retailer-Stackelberg • Centralized problem • Decentralized problem	• MLOR rule (fixed or flexible) is a decision variable	• Supplier-to-retailer • Retailer-to-consumer	• Deterministic, age and price dependent

Table 3. Summary of literature on the MLOR rule

2.3 Summary of existing literature

The literature review reveals that Game Theory has been extensively applied to model and solve supply chain issues. In Green Supply Chain Management papers, 80% employ the Stackelberg model, with 59% assuming the manufacturer as the leader. Most of these studies do not incorporate competition and consider deterministic demand (Agi et al., 2021). This work aligns with most existing literature but diverges in the power structure of the SC, considering the retailer as the dominant actor based on the current market scenario. GT applications for coordinating the SC through discount mechanisms are well-established. However, only two papers examine the Retailer-Stackelberg game (Esmaeili et al., 2009; Kazemi & Saeedmohammadi, 2016), and just one introduces a retailer-to-consumer discount alongside the supplier-to-retailer discount (Kazemi & Saeedmohammadi, 2016). While GT methodology is commonly used to address perishability issues, and discounts are often applied to tackle this problem, no papers consider the retailer as the leader in Perishable Food Supply Chains (PFSC) and only one proposes the retailer-to-consumer discount (Chen et al., 2019). Additionally, contractual policies are rarely analyzed in these SCs.

Regarding the MLOR rule, the literature is nascent and limited. Existing studies examine the effects of a flexible MLOR rule, suggesting its benefits for reducing waste and increasing profits. However, further insights are needed to persuade retailers to transition from a fixed MLOR rule to a flexible one, beyond the shifting cost of the contractual policy. This thesis advances GT applications in the PFSC literature by developing a Stackelberg model with a retailer-leader scenario and addressing the underexplored issues of food waste at the supplier-retailer interface and existing contractual policies. Additionally, it expands on MLOR rule studies by integrating a discount system that functions as a revenue-sharing mechanism across the SC, from supplier to retailer and retailer to consumer, enhancing SC profitability and consumer surplus. The aim is to provide producers and retailers with managerial insights to improve SC performance in a scenario with demand dependent on product age and price.

3. METHODOLOGY

In this section, the methodology to propose a new interaction and to assess its impact on the SC is presented. The problem is described in section 3.1, the Stackelberg game developed to represent it and the optimization model formulated to solve it are presented respectively in section 3.2 and 3.3.

3.1 Problem description

The supply chain under study is two-tiered, consisting of a manufacturer/supplier and a retailer. The supplier is a small local manufacturer who exclusively deliver its single product to the retailer, a large supermarket that resells them to the end consumer, which holds significant bargaining power. The product in question is a fresh, perishable food item with a shelf life (sl) of 3 days (e.g., fruits, vegetables, bread). This product ages over the time horizon (T) from its production ($a=0$) until it reaches its shelf life ($a=sl$). The time horizon considered is three periods. Any product produced by the supplier but not delivered to the retailer due to non-compliance is considered surplus food. This surplus is diverted to an alternative channel (e.g., animal feed, non-food production), which generates a revenue for the producer (salvage value) but not a profit, as the revenue from these channels is lower than the production cost. Moreover, food products not used for human consumption do not realize their full potential use, representing a loss at the supplier-retailer interface. The retailer enforces a fixed MLOR rule, where only goods with a remaining life of at least 66% of their total shelf life are deemed compliant and accepted for sale to the final consumer (Santos et al., 2022). For a perishable product with a three-days shelf life and a three-periods time horizon, compliance with the MLOR rule means the product must reach the retailer within one day of age. This stringent rule forces the producer to manufacture in each period to meet the retailer's demand and freshness requirements due to the replenishment lead time, resulting in high setup costs and food surplus. To incentivize the retailer to cooperate and relax the MLOR rule, the manufacturer offers a discount on the entire order if the retailer accepts products with a lower remaining life. This flexible MLOR rule allows the MLOR value to be adjusted below the fixed 66%. Upon receiving the discount, the retailer chooses the selling price of products for end consumers. Consumer demand is deterministic and dependent on price and freshness. Offering fewer fresh products at a lower selling price may help sell all products before they expire, thus reducing food waste at the retailer. The objective of this work is to compare the proposed flexible MLOR rule with the traditional scenario, evaluating its impact on the profitability of both parties, as well as on food surpluses at the producer. The retailer's profit is expected to benefit from the discount system, providing a valuable incentive to cooperate with the manufacturer through the flexible MLOR rule.

3.1.1 Assumptions

The assumptions used in the Stackelberg model, and the centralized optimization model are as follows:

I. Supply chain structure:

- A two-level supply chain comprising one supplier and one retailer with a single product is considered.
- There is no competition.

II. Product characteristics:

- The product is a fresh perishable food with a limited shelf life of three periods. Freshness decreases over its shelf life.

III. Time horizon

- The time horizon is three periods, with each period equal to one day.

IV. Inventory control policy

- The inventory control policy used by the retailer and the manufacturer is a periodic-review inventory model, where the inventory level is reviewed daily to decide how much to produce or to order to replenish inventory.
- Both the manufacturer and the retailer use a First-In First-Out (FIFO) method to manage and deplete its inventory.

- The producer's inventory is initialized at the beginning of each period. Production by the manufacturer occurs in period t, with goods delivered at the beginning of period $t+1$, leading to inventory costs incurred by the manufacturer until delivery.
- The retailer's inventory is accounted for at the end of each period. Goods are received by the retailer in period t and sold in the same period t, resulting in inventory costs only for goods delivered in t and sold in $t+1$.

V. Inventory initialization

- Both the manufacturer's and the retailer's warehouses start with zero inventory at the beginning of the time horizon.

VI. Lead time:

- The production lead time for the manufacturer is zero.
- The lead time between the manufacturer and the retailer is one period.
- Orders by the retailer and production by the manufacturer take place in period t, with delivery occurring in $t+1$.

VII. Demand characteristics:

- Demand is deterministic but dependent on both price and freshness. Consumers' willingness to buy decreases as the age (a) and the price (r_a) of the product increase. This relationship is defined as:

$$d_{a,t} = d_t - \alpha \times (r_a - r_c) - \beta \times (a - a_c) \qquad (1)$$

where d_t is the deterministic consumer demand for products with compliant age sold at standard price; r_c and a_c are the reference points for compliant price and age; α and β are the sensitivity of consumers to price and age, respectively. Consumers find it rational to pay r_c for a product with age a_c. Therefore, the demand $d_{a,t}$ for a product with age a in the period t is a function of the reference price and age, as well as the selling price and age.

VIII. Production lot size:

- The manufacturer's minimum production lot size is greater than the retailer's demand for one period.

IX. Fixed MLOR rule

- A fixed MLOR rule stipulates that products must have 66% of their shelf life remaining upon delivery to the retailer, based on Santos et al. (2022)

X. Non-compliant products:

- Products considered non-compliant with the freshness requirement are classified as food surplus at the producer level. These are sent to alternative channels and have a salvage value (s) lower than the production cost (c).

XI. Expired products:

- Products that expire before being sold are classified as outdated at the retailer, who bears their disposal cost (o).

3.1.2 Sequence of Decisions and Events

The sequence of decisions and events for the manufacturer in each period is as follows:

1. Decision: At the beginning of each period t, the manufacturer decides the quantity to be produced (q_t).
2. Event: The manufacturer's inventory is updated with the freshly produced items, which will be available for delivery in the next period, while products delivered in the previous period are deducted ($IP_{a,t}$).
3. Decision: The manufacturer fulfills the retailer's order from the previous period with the available inventory based on the required MLOR ($R_{a,t}$).
4. Event: Products that do not meet the MLOR requirement are sent to alternative channels ($A_{a,t}$).

The sequence of decisions and events for the retailer is as follows:

1. Event: At the beginning of every period, the retailer receives the shipment of its order from the previous period ($R_{a,t}$).
2. Event: The demand from end consumers is realized (d_t).
3. Event: The retailer removes the outdated units (O_t).
4. Event: The retailer updates the inventory ($IR_{a,t}$).
5. Decision: At the end of the period, the retailer makes its order decision for the following period (Q_t), considering the remaining inventory and the consumer demand.

Figure 2 illustrates the sequence of decisions and events for both the retailer and the manufacturer, with decisions highlighted in red and events in green.

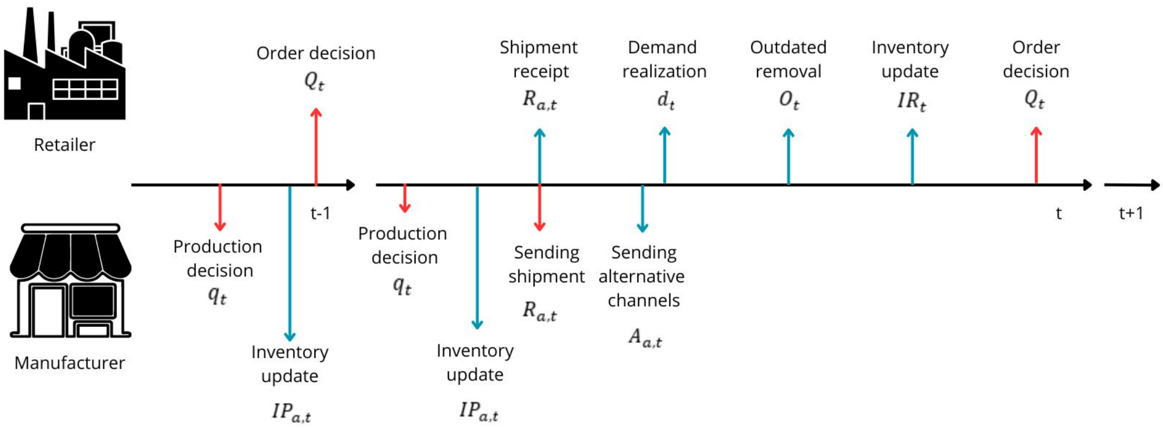

Figure 2. The sequence of decisions and events for the retailer and the manufacturer

3.1.3 The Stackelberg Game

This section describes the game theory model developed to represent the interaction between the retailer and the manufacturer. In line with existing models in the literature, it employs a noncooperative dynamic framework based on the Stackelberg game. The analysis focuses on a two-level supply chain with an imbalanced power structure, where the retailer acts as the leader and the manufacturer as the follower, reflecting the reality of most FSCs (Canali et al., 2014; Devin & Richards, 2018; Maglaras et al., 2015). The model assumes deterministic demand, excludes competition, and the solution is found through the maximization of individual profit for supply chain members. Food surplus reduction considerations are derived indirectly.

The objective is to model a collaborative scenario as an alternative to the one in which the retailer dominates the commercial relationship using a fixed MLOR rule as contractual policy. To achieve this, three incentives that the producer can offer to the retailer are evaluated to encourage acceptance of fresh products that do not meet the fixed MLOR threshold. These incentives aim to provide an optimal solution involving a flexible MLOR rule instead of a fixed one. The three incentives are as follows:

1. A discount on the entire lot delivered in period t whenever at least one non-compliant unit is included.
2. Delivery of a smaller lot than expected to prevent products from expiring at the retailer before being sold.
3. Offer a smaller lot quantity and a discount on all units in the delivered lot whenever at least one non-compliant unit is included.

Upon receiving products from the producer, the retailer can choose one of the following selling models:

1. A standard selling price (equal to the reference price in the demand function) for all units (both compliant and non-compliant).
2. Standard selling price for all units with compliant age and discounted selling price for units with non-compliant age.

The first model applies automatically when no discount is received from the producer, as the retailer can lower the selling price only if its purchase cost is reduced by the discount received.

Two important aspects enhance the efficiency of the proposed discount model:

- Offering products with a remaining life below the fixed MLOR threshold at a standard price will decrease final demand, according to the demand function (equation 1). The retailer can thus counterbalance this demand decrease by reducing the price of older products.
- The producer’s discount applies to all units delivered to the retailer when at least one non-compliant unit is included. This allows the retailer to lower the selling price while still benefiting from the producer’s incentive. If the producer's discount to the

retailer was to be applied only to non-compliant units, the retailer would face a dilemma: sell at a standard price and risk decreased demand and expired products or sell at a discounted price and lose the benefit from the producer's incentive (assuming equal discounts from the producer to the retailer and from the retailer to the final consumer). This case is outside the scope of this research.

After outlining the key points of the model, the interaction between the players is analyzed. The retailer (denoted as “R”), acting as the Stackelberg leader, can propose either a fixed MLOR agreement or a new flexible MLOR agreement to the producer (denoted as “P”) as a take-it-or-leave-it offer. In the fixed MLOR scenario, the producer accepts the agreement if it can achieve a positive profit and if its inventory complies with the rule. In the flexible scenario, the producer can either delivery only compliant products or deliver both compliant and non-compliant products, offering one of the three incentives. In both scenarios, the producer accepts the agreement only if it is profitable to it. At the end of the game, the retailer sets the selling price, choosing between the standard price and a discounted price (if he has received a discount from the producer). The Stackelberg game between the retailer and the manufacturer is illustrated in Figure 3.

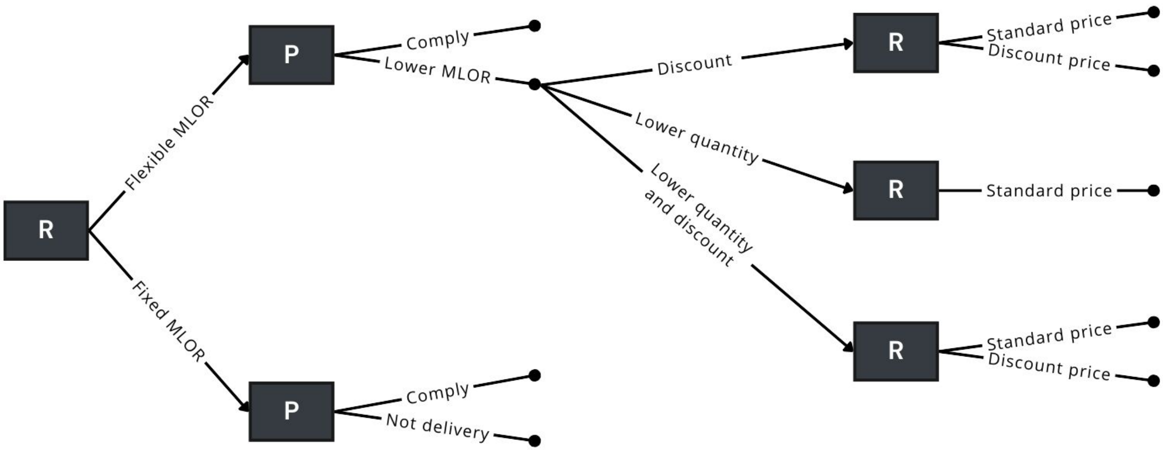

Figure 3. The Stackelberg game between the retailer and the producer

Among the scenarios depicted in Figure 2, this thesis focuses exclusively on the scenario where the manufacturer offers a discount to the retailer as an incentive, and the retailer, in turn, sets the selling price to consumers according to item's age. The thesis deepens the first among the three incentives, as the concept of manufacturer-to-retailer discounts has been extensively explored in the literature and has proven to be an effective mechanism for supply chain coordination (Chiang et al., 1994; Karray & Surti, 2016; Parlar & Wang, 1994) and a step towards collaborative interaction (Mohamadi et al., 2023). Among the retailer's options, the discounted selling price is further analyzed because it can reduce waste due to the expiration of unsold products. This structured discount system is expected to enable both the manufacturer and the retailer to achieve greater profits compared to a scenario where the retailer imposes a fixed MLOR rule. Additionally, it is expected to contribute to reduce food surplus at the producer level. The main focus of this work is on the retailer's profit, given the retailer's dominant role in the supply chain and its power to implement policies. The game that will be analyzed is illustrated in Figure 4.

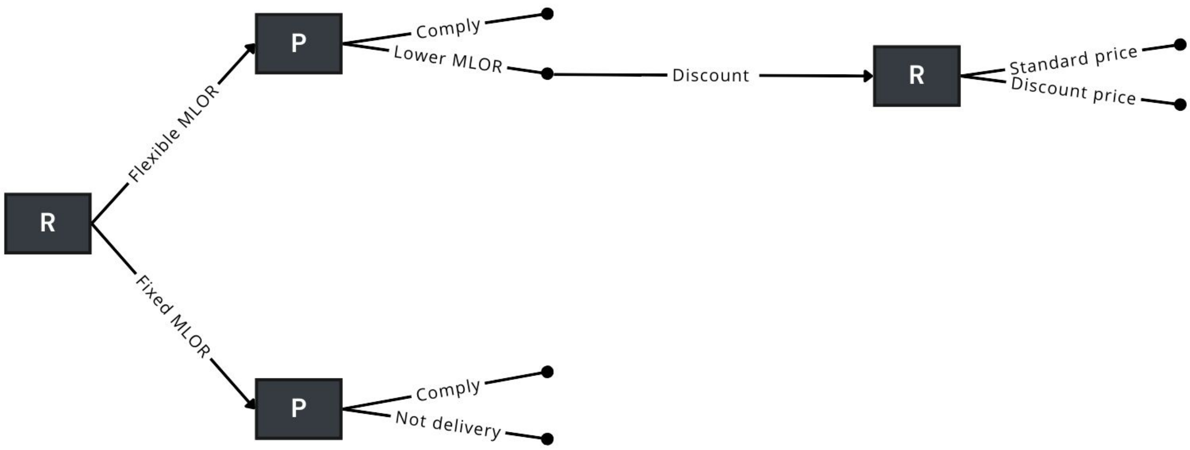

Figure 4. The proposed reduced Stackelberg game

Using backward induction, the retailer maximizes its profit per period by optimizing the type of contract, ensuring that the manufacturer also achieves a positive profit. Both parties make decisions to maximize their immediate profit function. The discount strategy, which results in a flexible MLOR rule, is illustrated in Figure 5.

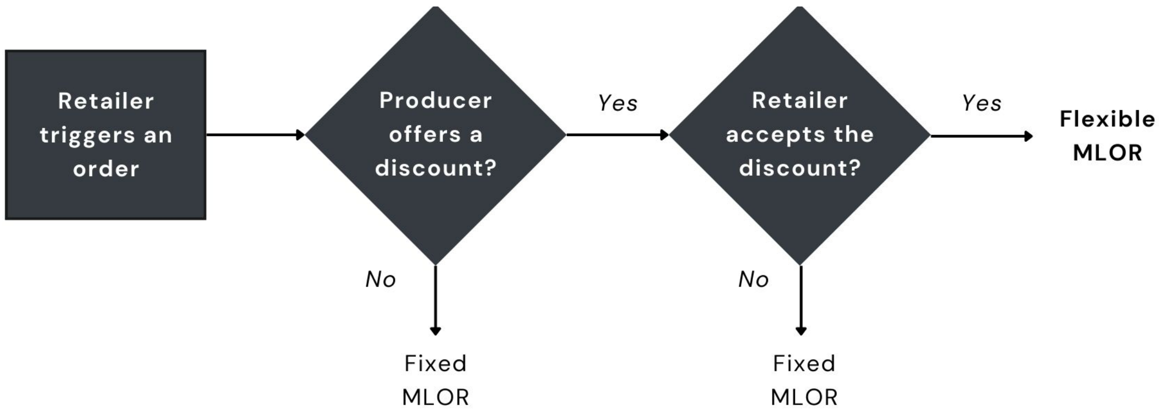

Figure 5. Discount strategy aims for a flexible MLOR rule

Considering a time horizon of three periods and a product with a shelf life of three days, the discount strategy can result in four distinct cases:

1. Only compliant products are delivered in each period, equivalent to apply a fixed MLOR rule without any discount.
2. Non-compliant products are delivered only in period 2, which implements a flexible MLOR rule.
3. Non-compliant products are delivered only in period 3, which implements a flexible MLOR rule.
4. Non-compliant products are delivered in both periods 2 and 3, resulting in a flexible MLOR rule.

These scenarios are developed under the assumptions in Section 3.1.1: the producer's inventory starts at zero, production begins in period zero, and the lead time to deliver products is one period (or one day). This setup means that only compliant products are available from the producer's inventory in period 1, with non-compliant products available for delivery starting from period 2. Figure 6 illustrates these four cases.

Details of the optimization model are provided in Section 3.2.

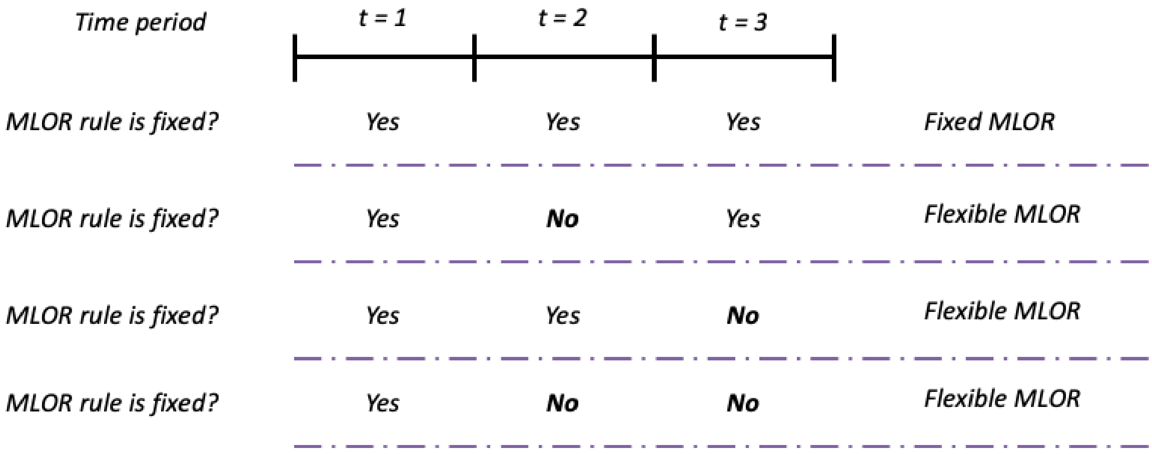

Figure 6. Alternative cases over a three-period time horizon

3.2 Mathematical model

The optimization model is developed based on the assumptions outlined in Section 3.1.1. Mathematical notations are detailed in Section 3.2.1, and the models formulation is provided Sections 3.2.2, 3.3.3, and 3.3.4.

3.2.1 Mathematical notations

This section presents the nomenclature used in the model. Data regarding the values assigned to parameters are provided in Appendix A.

Indexes and sets	
$t \in T, T = \{0, \ldots, T\}$	set of periods
$a \in A, A = \{0, \ldots, sl\}$	set of ages of product, $a \leq t$

Parameters	
c	unitary production cost
d_t	consumers' demand in period t
f	fixed ordering cost of retailer

h	unitary inventory holding cost at producer
h’	unitary inventory holding cost at retailer
l	minimum lot-size
M	large number
MLOR	MLOR rule = 66% of remaining shelf life
o	cost of waste disposal at retailer
p_a	unitary revenue of producer per product with age a
r_a	unitary revenue of retailer per product with age a
s	unitary salvage value of producer (from alternative channels)
sl	shelf life
u	production setup cost
T	time horizon

Decision variables	
Producer	
$disc_t$	discount in period *t*
q_t	quantity produced in period *t*
$R_{a,t}$	quantity delivered to the retailer with age *a* in period *t*
Y_t	production setup in period *t*
X_t	quantity of non-MLOR compliant products delivered to the retailer in period *t*
Retailer	
Q_t	quantity ordered at the beginning of period *t*
β_t	1 if an order is made in period *t*, 0 otherwise

Other variables	
Producer	
$AC_{a,t}$	products with age *a* toward the alternative channel in period *t*
$IP_{a,t}$	inventory of producer with age *a* at the beginning of period *t*
Rd_t	economic discount to the retailer in period *t*
Retailer	
$d_{a,t}$	consumers’ demand for products with age *a* in period *t*

$IR_{a,t}$	inventory of the retailer with age a at the end of period t
IR_t	total inventory of the retailer at the end of period t
O_t	total amount of expired products in period t

3.2.2 Centralized optimization model

This section introduces the objective function and constraints of the centralized optimization model, which is the core of this work. The model aims to find the optimal solution that maximizes the total profit of the supply chain, in line with the objective of the proposed collaborative model to enhance profitability and reduce waste. However, this thesis primarily focuses on analyzing the retailer's benefits, necessitating comparisons to derive managerial insights. Therefore, the problem is also optimized using two decentralized models: one that maximizes the retailer's profit (Section 3.2.3) and another that maximizes the producer's profit (Section 3.2.4).

$$\max \ \sum_t^T [\sum_a^A (r_a \times d_{a,t}) - h' \times IR_t - p_1 \times \sum_a^A R_{a,t} + Rd_t - f \times \beta_t - o \times O_t] + \sum_t^T [(p_1 \times \sum_a^A R_{a,t} - Rd_t) - h \times \sum_a^A (IP_{a,t} - R_{a,t} - AC_{a,t}) - u \times Y_t - c \times q_t + s \times \sum_a^A AC_{a,t}] \qquad (2)$$

$$\sum_a^A R_{a,t} \leq Q_{t-1} \qquad \forall\, t \in T, t > 0 \qquad (3)$$

$$IP_{0,t} = q_t \qquad \forall\, t \in T \qquad (4)$$

$$IP_{a,t} = IP_{a-1,t-1} - R_{a-1,t-1} - AC_{a-1,t-1} \qquad \forall\, a \in A, t \in T, a \geq 1, t \geq 1 \ (5)$$

$$0 = IP_{a,T} - R_{a,T} - AC_{a,T} \qquad \forall\, a \in A \qquad (6)$$

$q_t \leq M \times Y_t$ $\forall$ t ∈ T (7)

$q_t \geq l \times Y_t$ $\forall$ t ∈ T (8)

$X_t = \sum_a^A R_{a,t}$ $\forall$ a ∈ A, a > (1-MLOR) * sl (9)

$disc_t \times M \geq X_t$ $\forall$ t ∈ T, t > 1 (10)

$Rd_t \leq (X_t + R_{1,t}) \times (p_1 - p_2)$ $\forall$ t ∈ T, t > 1 (11)

$Rd_t \geq \left(X_t + R_{1,t}\right) \times (p_1 - p_2) - (1 - disc_t) \times M$ $\forall$ t ∈ T, t>1 (12)

$Rd_t \leq X_t \times M$ $\forall$ t ∈ T, t > 1 (13)

$\sum_a^A d_{a,t} = d_t$ $\forall$ a ∈ A, t ∈ T (14)

$Q_t \geq d_{t+1} - IR_t$ $\forall$ t ∈ T, t < T (15)

$Q_t \leq \beta_t \times M$ $\forall$ t ∈ T (16)

$$IR_{a,t} = IR_{a-1,t-1} + R_{a,t} - d_{a,t} \qquad \forall\ a \in A, t \in T, t > 0, a > 0 \qquad (17)$$

$$IR_t = \sum_a^A Ir_{a,t} - O_t \qquad \forall\ t \in T, t > 0, a > 0 \qquad (18)$$

$$O_t = IR_{sl,t} \qquad \forall\ t \in T \qquad (19)$$

$$O_t = 0 \qquad \forall\ t \in T, t < sl \qquad (20)$$

$$IR_{a,0} = 0 \qquad \forall\ a \in A \qquad (21)$$

$$IR_{0,t} = 0 \qquad \forall\ t \in T \qquad (22)$$

$$d_{a,0} = 0 \qquad \forall\ a \in A \qquad (23)$$

$$AC_{0,t} = 0 \qquad \forall\ t \in T \qquad (24)$$

$$AC_{a,t} = 0 \qquad \forall\ a \in A, t \in T, a > t \qquad (25)$$

$$R_{0,t} = 0 \qquad \forall\ t \in T \qquad (26)$$

$$R_{a,t} = 0 \qquad \forall\ a \in A, t \in T, a > t \qquad (27)$$

$$Y_T = 0 \qquad (28)$$

$$\beta_T = 0 \qquad (29)$$

$$X_t = 0 \qquad t = 0,1 \qquad (30)$$

$$disc_t = 0 \qquad t = 0,1 \qquad (31)$$

$$Rd_t = 0 \qquad t = 0,1 \qquad (32)$$

$$AC_{a,t},\ IP_{a,t},\ q_t,\ R_{a,t},\ Rd_t,\ Q_t,\ IR_{a,t},\ d_{a,t},\ O_t,\ X_t \geq 0 \qquad \forall\ a \in A, t \in T \ (33)$$

$$Y_t,\ disc_t,\ \beta_t \in \{0,1\} \qquad \forall\ t \in T \qquad (34)$$

Objective function (2) maximizes the total profit over the time horizon T. The first term represents the retailer's sales revenues, followed by the retailer's inventory costs, purchasing costs, fixed ordering costs, and outdated costs. Then, it includes the producer's revenues from retail, inventory holding, setup, and production costs and revenues from alternative channels.

Producer's profits are derived from products sold through retail and alternative channels minus discounts provided to the retailer for the delivery of non-compliant products, inventory holding costs, and total production cost (setup plus production).

Retailer's profits are calculated based on sales revenue minus inventory, purchasing, outdated, and ordering costs. The purchase cost is adjusted by discounts offered by the producer.

Constraint (3) limits the quantity shipped to the retailer in each period to be at most equal to the quantity requested in the previous period (when the order is triggered).

Constraints (4) to (6) manage the producer's inventory balance (quantity and age) over time. Constraint (4) relates production quantity to inventory, constraint (5) enforces FIFO inventory depletion, and constraint (6) ensures zero inventory at the end of the time horizon.

Constraint (7) ensures setup occurs whenever production happens.

Constraint (8) establishes a minimum production quantity (lot-size).

Constraints (9) to (10) model the discount mechanism from producer to retailer. Constraint (9) computes the quantity of non-compliant products delivered, constraint (10) activates the discount binary variable, constraint (11) calculates the discount amount offered, constraint (12) allows for the discount to be zero, and constraint (13) ensures no discount when non-compliant products are absent. Constraint (14) allocates total consumer demand among products with different ages.

Constraint (15) sets the minimum number of products ordered by the retailer, based on inventory and future demand.

Constraint (16) ensures fixed ordering costs occur when an order is placed.

Constraints (17) and (18) update retailer's inventory within the time horizon.

Constraint (19) equates outdated to inventory reaching its shelf life.

Constraint (20) ensures that outdated are equal to zero when the shelf life is not reached.

Constraint (21) and (22) initialize the retailer's inventory and manage flow into warehouse.

Constraints (23) ensures that there is no demand of any products in period 0.

Constraints (24) and (25) ensure that no products are sent to the alternative channel to zero in period 0 and for products not yet aged to the current period.

Constraints (26) and (27) ensure that no delivery can occur to the retailer in advance of period 1 and for products not yet aged to the current period.

Constraints (28) and (29) prevent production and ordering in the last period.

Constraints (30) to (32) ensure that non-compliant products, discount variables, and discount amount are zero in periods 0 and 1.

Constraints (33) and (34) define the domain for decision variables.

3.2.3 Retailer's decentralized optimization model

This section provides the objective function of the retailer's decentralized model. The assumptions and the constraints are the same as those used in the centralized model.

$$\max \quad \sum_t^T [\sum_a^A \left(r_a \times d_{a,t}\right) - h' \times IR_t - \ p_1 \times \sum_a^A R_{a,t} + Rd_t - f \times \beta_t - o \times O_t] + 0.001 \times (-h * \sum_a^A \left(IP_{a,t} - R_{a,t} - AC_{a,t}\right) - u * Y_t - c * q_t) \qquad (35)$$

The objective function maximizes the retailer's revenues net of inventory holding costs, ordering costs, and outdated. The second term ensures the model provides a rational solution for the producer as well.

3.2.4 Producer's decentralized optimization model

This section provides the objective function of the producer's decentralized model. The assumptions are the same as those used in the previous models, and the constraints are nearly identical. Differences in constraints are detailed in Appendix B.

$$\max \quad \sum_t^T [(p_1 \times \sum_a^A R_{a,t} - Rd_t) - h \times \sum_a^A \left(IP_{a,t} - R_{a,t} - AC_{a,t}\right) - u \times Y_t - c \times q_t + s \times \sum_a^A AC_{a,t}] \qquad (36)$$

The objective function maximizes the producer's revenues net of discount to the retailer, inventory setup costs, and production costs.

4. RESULTS AND DISCUSSION

The centralized model and the two decentralized models are implemented in Python 3.12 and solved with Gurobi 11.0.1 on a computer equipped with an Intel Core i5 processor running at a base speed of 1.80 GHz, with a runtime of 0.01 seconds. Five different scenarios are investigated based on the three optimization models, as shown in Table 4. The parameters used in this case study are detailed in Appendix A. The optimal solutions and outputs are presented and discussed in Section 3.1, 3.2, and 3.3.

Scenario	A	B	C	D	E
Power structure	Balanced	Balanced	Retailer-dominated	Retailer-dominated	Producer-dominated
O.F.	Total profit maximization	Total profit maximization	Retailer's profit maximization	Retailer's profit maximization	Producer's profit maximization
Collaboration	Yes	Yes	No	No	No
MLOR rule	Decision variable	Fixed	Decision variable	Fixed	Decision variable

Table 4. Five proposed scenarios

Collaboration is considered to occur when the problems faced by both parties are integrated, and the O.F. maximizes the total profit of the supply chain without favoring either actor. When the MLOR rule is treated as a decision variable, the model has the flexibility to adopt either the flexible MLOR rule with a discount strategy or the fixed rule, selecting the option that maximizes the O.F. Conversely, in scenarios with a fixed MLOR rule, this fixed rule is strictly enforced through constraints.

4.1 SCENARIO A - Centralized model: results and analysis

The optimal solution and the output from the centralized model are depicted in Table 5, Table 6, and Table 7.

SCENARIO A	**PRODUCER**					**age**	**0**	**1**	**2**	**3**	
time	q	Y	disc	X	Rd						
0							15	-	-	-	IP
	15	1	-	-	-		-	-	-	-	R
							-	-	-	-	AC
1							15	15	-	-	IP
	15	1	-	-	-		-	10	-	-	R
							-	-	-	-	AC
2							-	15	15	-	IP
	-	-	1	5	20		-	15	5	-	R
							-	-	-	-	AC
3							-	-	-	-	IP
	-	-	-	-	-		-	-	-	-	R
							-	-	-	-	AC

Table 5. Producer's optimal solution in scenario A

SCENARIO A	RETAILER		age	0	1	2	3	
time	Q	β						
0	10	1		- -	- -	- -	- -	IR d
1	20	1		- -	- 10	- -	- -	IR d
2	-	-		- -	10 5	- 5	- -	IR d
3	-	-		- -	- -	- 10	- -	IR d

Table 6. Retailer's optimal solution in scenario A

The optimization of the centralized model reveals that maximizing the total SC profit in this context requires relaxing the threshold imposed by the fixed MLOR rule, allowing the delivery of non-compliant products. This relaxation is triggered by the activation of the discount decision variable ($disc_t$) in period 2. During this period, the economic discount offered to the retailer (Rd_t) amounts to 20 euros, and 5 units of non-compliant products (X_t) are delivered from the producer.

To meet consumer demand ($d_{a,t}$) over three periods, the retailer places two orders (Q_t, in period 0 and 1), while the producer initiates production twice (q_t, in period 0 and 1). Products sold with age 1 to end consumers ($d_{1,1}$ and $d_{1,2}$) are sold at the standard price, while products with age 2 ($d_{2,2}$ and $d_{2,3}$) are sold at a discounted price.

MLOR rule	Flexible
OF	54
Retailer	
Revenues from consumers	142.50
Discount from producer	20
Holding cost	5
Purchase cost	120
Fixed ordering cost	10
Outdated	0
Profit	27.5
Producer	
Revenues from retailer	120
Discount to retailer	20
Revenues from AC	0
Setup cost	10
Production cost	60
Holding cost	3.50
Surplus food	0
Profit	26.5

Table 7. Scenario A output

The objective function value (OF) for the centralized model is 54 euros, indicating the overall performance of the supply chain under the centralized optimization approach. This value is achieved using the flexible MLOR rule, as indicated in **Errore. L'origine riferimento non è stata trovata.**. The retailer's net purchase cost after the discount from the producer is

100 euros. Due to the deterministic demand scenario, there are no outdated products, as the demand for each period is known and fulfilled.

While the relaxation of the MLOR value may increase expired products in an actual market scenario (Mohamadi et al., 2023), the discounted pricing strategy can mitigate this food waste to some extent. The flexible MLOR approach helps in avoiding food surplus (AC) at the producer level.

The optimal solution to the centralized problem, incorporating the flexible MLOR rule, proves beneficial for both the producer and the retailer, ensuring positive and balanced profitability and eliminating food waste at the supplier-retailer interface.

4.2 SCENARIO B - Centralized model with fixed MLOR rule: results and analysis

The centralized model is also solved enforcing a fixed MLOR rule scenario. The optimal solution and output are provided in Table 8, Table 9, and Table 10.

SCENARIO B	**PRODUCER**					**age**	**0**	**1**	**2**	**3**	
time	q	Y	disc	X	Rd						
0							15	-	-	-	IP
	15	1	-	-	-		-	-	-	-	R
							-	-	-	-	AC
1							15	15	-	-	IP
	15	1	-	-	-		-	15	-	-	R
							-	-	-	-	AC
2							-	15	-	-	IP
	-	-	-	-	-		-	15	-	-	R
							-	-	-	-	AC

3	-	-	-		-		- - -	- - -	- - -	- - -	IP R AC

Table 8. Producer's optimal solution in scenario B

SCENARIO B	**RETAILER**		**age**	**0**	**1**	**2**	**3**	
time	Q	β						
0	15	1		- -	- -	- -	- -	IR d
1	15	1		- -	5 10	- -	- -	IR d
2	-	-		- -	10 5	- 5	- -	IR d
3	-	-		- -	- -	- 10	- -	IR d

Table 9. Retailer's optimal solution in scenario B

When the fixed MLOR rule is enforced in the integrated (centralized) problem, only the freshest products are delivered to the retailer, and no discount ($disc_t$) is offered by the producer. Two orders are placed to meet consumer demand, and two production setups occur at the producer. Products sold with age 1 to end consumers ($d_{1,1}$ and $d_{1,2}$) are sold at the standard price, while products with age 2 ($d_{2,2}$ and $d_{2,3}$) are sold at a discounted price.

MLOR rule	Fixed
OF	52
Retailer	
Revenues from consumers	142.50
Discount from producer	0
Holding cost	7.50
Purchase cost	120
Fixed ordering cost	10
Outdated	0
Profit	5
Producer	
Revenues from retailer	120
Discount to retailer	0
Revenues from AC	0
Setup cost	10
Production cost	60
Holding cost	3
Surplus food	0
Profit	47

Table 10. Scenario B output

The OF value for the centralized model in this scenario is 52 euros. The optimal solution results in very imbalanced profits between the retailer and the producer, with the retailer achieving almost one-tenth of the producer's profit. This outcome highlights the unfeasibility of this model in the actual market, where the retailer typically has greater bargaining power and would not accept such an agreement.

The infeasibility arises from two key factors:

1. The fixed MLOR rule is enforced in a centralized model, giving equal priority to the producer and retailer's profits, which is inconsistent with real-world dynamics.
2. The fixed MLOR rule implies no producer-to-retailer discount, yet in the proposed scenario, the retailer-to-consumer discount remains active for non-compliant products. This decision aligns with the demand function, as removing the discount would result in lost demand for the retailer. Therefore, maintaining the discount is essential to preserve deterministic demand.

While this assumption on the discount to consumer penalizes the retailer, it realistically compensates for the loss of demand that would occur in a fixed MLOR scenario without a discount for end consumers. Waste at the retailer remains zero due to deterministic demand, and surplus at the producer is zero due to centralized optimization.

Although this scenario is unlikely, its analysis allows comparing flexible and fixed MLOR rules in a centralized problem. The results indicate that the overall profit of the supply chain is higher with a flexible MLOR rule, and this profit is better distributed among players. This suggests that such an agreement could enhance collaboration and integration within the supply chain. The retailer benefits from a flexible MLOR rule by reducing holding costs, consistent with (Santos et al., 2022), and purchasing costs. Conversely, the producer faces higher holding costs and lower revenues from the retailer. As the MLOR is lowered, the producer's and retailer's inventory costs move in opposite directions: older products flowing to the retailer allow the producer to hold more stock before transferring it to the retailer.

4.3 SCENARIO C - Retailer's decentralized model: results and analysis

The core of this thesis is the maximization of the retailer's profit. This objective function is analyzed under two conditions: when the retailer can choose between a fixed and flexible MLOR rule (scenario C), and when the fixed rule is imposed (scenario D). These scenarios closely resemble the actual supply chain (SC), where there is no collaboration, the retailer holds the most bargaining power, and decisions are made solely to maximize its own profit.

Scenario C evaluates the most advantageous policy for the retailer when the producer's profit is not considered, with results presented in Table 11, Table 12, and Table 13. Scenario D results are presented in Section 4.4

SCENARIO C	**PRODUCER**					**age**	**0**	**1**	**2**	**3**	
time	q	Y	disc	X	Rd						
0							15	-	-	-	IP
	15	1	-	-	-		-	-	-	-	R
							-	-	-	-	AC
1							15	15	-	-	IP
	15	1	-	-	-		-	10	-	-	R
							-	4	-	-	AC
2							15	15	1	-	IP
	15	1	1	1	10		-	9	1	-	R
							-	5	-	-	AC
3							-	15	1	-	IP
	-	-	1	1	10		-	9	1	-	R
							-	6	-	-	AC

Table 11. Producer's optimal solution in scenario C

SCENARIO C	**RETAILER**		**age**	**0**	**1**	**2**	**3**	
time	Q	β						

0	15	1		- -	- -	- -	- -	IR d
1	15	1		- -	5 10	- -	- -	IR d
2	-	-		- -	10 5	- 5	- -	IR d
3	-	-		- -	- -	- 10	- -	IR d

Table 12. Retailer's optimal solution in scenario C

The solution reveals that relaxing the MLOR is the most profitable choice for the retailer. As expected, the retailer takes advantage of the discount opportunity by ordering only one non-compliant unit in each period to receive a discount on the entire lot delivered. The discount is activated in period 2 and 3, totaling 20 euros, with the retailer receiving two non-compliant units.

Three orders are placed, and three setups occur at the producer. Consumer demand is satisfied largely with fresher products, except for the two non-compliant units. In scenarios A and B, food waste at the supplier-retailer interface ($AC_{a,t}$) was absent, while it emerges in this decentralized scenario because maximizing the retailer's profit does not prioritize minimizing food waste.

MLOR rule	Flexible
OF	34
Retailer	
Revenues from consumers	149

Discount from producer	20
Holding cost	0
Purchase cost	120
Fixed ordering cost	15
Outdated	0
Profit	34
Producer	
Revenues from retailer	120
Discount to retailer	20
Revenues from AC	15
Setup cost	15
Production cost	90
Holding cost	4.7
Surplus food	15
Profit	5.3

Table 13. Scenario C output

The model's output, aligned with the objective function (OF), leads to high profits for the retailer at the expense of the producer. Several key insights arise from these outcomes:

1. The proposed flexible MLOR rule is more advantageous for the retailer compared to the fixed rule, even in a non-cooperative scenario.
2. The flexible MLOR rule poses a risk for the producer when the retailer holds significant bargaining power. However, this scenario is unlikely to occur. For instance, if the retailer orders only a small fraction of non-compliant units per period, the producer is unlikely to offer discounts on the entire batch delivered. According to the strategi dynamic depicted in Figure 3 and Figure 4, the producer would prefer to comply with the MLOR each period, delivering only fresher products. This scenraio is discussed further in Section 4.4.

3. The total profit for the SC in scenario C is 39.3, significantly lower than that achieved in scenario A. Despite this, the retailer’s profit increases from 27.5 to 34 euros, compared to scenario A, achieved by fully exploiting bulk discounts at the producer’s expenses. However, it is crucial to note that the decision to offer discounts remains at the discretion of the producer.
4. The flexible MLOR rule has the potential to enhance retailer's profit, contingent upon effective collaboration between all parties involved. Both the retailer and producer must align on strategies to maximize its benefits.

4.4 SCENARIO D - Retailer’s decentralized model with fixed MLOR rule: results and analysis

Maximizing the retailer’s profit under the fixed MLOR rule as a contractual policy best represents current real-world conditions. The corresponding results are shown in **Errore. L'origine riferimento non è stata trovata.** and **Errore. L'origine riferimento non è stata trovata.**.

SCENARIO D	**PRODUCER**					**age**	**0**	**1**	**2**	**3**	
time	q	Y	disc	X	Rd						
0	15	1	-	-	-		15 - -	- - -	- - -	- - -	IP R AC
1	15	1	-	-	-		15 - -	15 10 5	- - -	- - -	IP R AC
2	15	1	-	-	-		15 -	15 10	- -	- -	IP R

							-	5	-	-	AC
3	-	-	-	-	-		- - -	15 10 5	- - -	- - -	IP R AC

Table 14. Producer's optimal solution in scenario D

SCENARIO D	**RETAILER**		**age**	**0**	**1**	**2**	**3**	
time	Q	β						
0	10	1		- -	- -	- -	- -	IR d
1	10	1		- -	- 10	- -	- -	IR d
2	10	1		- -	- 10	- -	- -	IR d
3	-	-		- -	- 10	- -	- -	IR d

Table 15. Retailer's optimal solution in scenario D

In a fixed MLOR scenario, the retailer opts to receive and sell only fresher products, with no discounts applied from the producer to the retailer or from the retailer to the consumer. Fixed ordering costs and setups costs are incurred in each period.

MLOR rule	Fixed

OF	15
Retailer	
Revenues from consumers	150
Discount from producer	0
Holding cost	0
Purchase cost	120
Fixed ordering cost	15
Outdated	0
Profit	15
Producer	
Revenues from retailer	120
Discount to retailer	0
Revenues from AC	15
Setup cost	15
Production cost	90
Holding cost	4.5
Surplus food	15
Profit	25.5

Table 16. Scenario D output

When the MLOR value is fixed, the retailer's objective function (OF) value is lower while the producer's profit is higher. This outcome may seem unexpected given the retailer's substantial bargaining power, but it highlights the economic advantage of flexibility for the retailer, aligning with Santos et al. (2022). It is important to note that these numerical results are highly dependent on parameter values. Therefore, the key insights come from analyzing the profits within each scenario for both parties, rather than comparing their absolute profits, which can vary significantly in real-world contexts.

Both the retailer and producer can benefit by moving from scenario D to scenario A. Profits of scenario D are realized whether the fixed rule is enforced or the retailer adopts a flexible MLOR, but the producer chooses to deliver only fresher products and does not offer the discount. Consequently, the retailer cannot exploit the proposed model to its advantage, as seen in scenario C. According to the Stackelberg game framework, the producer will only implement the discount strategy if it is beneficial for them. Thus, despite the retailer's significant bargaining power, it must consider the producer's profit to reach a feasible equilibrium.

The total profit in this scenario is 40.5, slightly higher than the previous case but still lower than in scenarios A and B. This indicates that collaboration within the supply chain can enhance overall profitability. Additionally, 15 units of surplus food are generated in both scenarios C and D, where only the retailer's profit is prioritized, while zero waste is produced in scenarios A and B, suggesting that collaboration can also be effective in reducing food surplus.

4.5 SCENARIO E - Producer’s decentralized model: results and analysis

Even though the producer’s decentralized model is an unlikely scenario under current market conditions, it is analyzed to determine if the producer can benefit from the proposed flexible rule. Previous results showed that the producer's profit is higher when the fixed rule is applied, so the scenario when the producer has maximum bargaining power is explored here.

SCENARIO E	**PRODUCER**					**age**	**0**	**1**	**2**	**3**	
time	q	Y	disc	X	Rd						
0	15	1	-	-	-		15 -	- -	- -	- -	IP R

							-	-	-	-	AC
1	15	1	-	-	-		15 - -	15 10 5	- - -	- - -	IP R AC
2	-	-	-	-	-		- - -	15 10 5	5 - -	- - -	IP R AC
3	-	-	1	10	10		- - -	- - 5	5 5 -	5 5 -	IP R AC

Table 17. Producer's optimal solution in scenario E

SCENARIO E	**RETAILER**		**age**	**0**	**1**	**2**	**3**	
time	Q	β						
0	10	1		- -	- -	- -	- -	IR d
1	10	1		- -	- 10	- -	- -	IR d
2	10	1		- -	- 10	- -	- -	IR d
3	-	-		- -	- -	- 5	- 5	IR d

Table 18. Retailer's optimal solution in scenario E

Maximizing the producer's profit involves relaxing the MLOR. Specifically, the producer offers a discount in period 3, amounting to 10 euros for 10 non-compliant units delivered. As expected, the producer chooses to deliver only compliant or non-compliant products in each period, preventing the retailer from benefiting from the entire lot discount. Orders are placed three times, while production occurs only twice. Consumer demand is satisfied with fresher products in periods 1 and 2, and with older products in period 3.

MLOR rule	Flexible
OF	35.5
Retailer	
Revenues from consumers	142.5
Discount from producer	10
Holding cost	4.5
Purchase cost	120
Fixed ordering cost	15
Outdated	0
Profit	17.5
Producer	
Revenues from retailer	120
Discount to retailer	10
Revenues from AC	0
Setup cost	10
Production cost	60
Holding cost	4.5

Surplus food	0
Profit	35.5

Table 19. Scenario E output

The SC total profit is 53 euros, very close to that achieved in scenarios A. However, despite the similarity in OF values, the distribution of profits among players is significantly different. This solution provides the producer with a much higher profit than the retailer, whereas in the centralized solution, the two profits are almost equal. To address this imbalance, revenue or cost-sharing mechanisms can be implemented in the supply chain (Agi et al., 2021; Chen et al., 2019; Li et al., 2021; Santos et al., 2022). A closer look at the two solutions reveals that both allow the flexible MLOR. The main difference is that in scenario A, a mix of compliant and non-compliant products is delivered in each period, enabling the retailer to benefit from the whole lot discount. In contrast, the producer's decentralized solution does not employ mixed lot deliveries, causing the retailer to lose that benefit. Thus, the entire lot discount may act as a revenue-sharing mechanism between the producer and the retailer, allowing both to achieve rational profit in a collaborative scenario.

Surplus food is avoided in scenario E as it is costly for the producer.

4.6 Scenarios summary

The results regarding profits, MLOR rules, and food surplus in each scenario are compared in Table 20. It is important to note that when the MLOR rule is not mandated to be fixed, its nature (fixed or flexible) becomes a decision variable of the model to achieve the optimal O.F.

Scenario	**A**	**B**	**C**	**D**	**E**
Oprimization	Centralized	Centralized	Retailer's decentralized	Retailer's decentralized	Producer's decentralized

MLOR rule	Flexible	Fixed (enforced)	Flexible	Fixed (enforced)	Flexible
Total profit	54	52	39.3	40.5	53
Retailer's profit	27.5	5	34	15	17.5
Producer's profit	26.5	47	5.3	25.5	35.5
Food surplus	0	0	15	15	15

Table 20. Results summary

4.7 Comparison of flexible and fixed MLOR rule

The aim of this section is to evaluate the impact of the flexible MLOR rule and the discount strategy in a collaborative scenario on the supply chain's profits and waste, and to compare it with the traditional setting of a fixed MLOR rule imposed by the retailer in a retailer-Stackelberg scenario.

Figure 7 clearly demonstrates that the newly proposed model of retailer-producer interaction effectively enhances the total profit of the supply chain, as well as the individual profits of both the retailer and the manufacturer, compared to the current fixed MLOR model (scenario D). In the traditional setting, the producer faces higher setup, production, and holding costs but enjoys higher profits from the retailer since no discount is offered. The flexible agreement allows the producer greater flexibility in fulfilling orders, resulting in lower costs. Interestingly, the producer's profit remains quite similar between the two scenarios. This underscores the value of the lot discount strategy introduced in the model: the cost reduction can be leveraged to offer a discount to the retailer as a form of revenue-sharing mechanism. This incentive benefits both the producer and the retailer, enhancing overall flexibility. The key insight is that the centralized optimal solution outperforms the retailer's decentralized optimal solution.

As anticipated, outdated products are not present at the retailer, and therefore this variable is not measured. This is a common assumption in papers addressing production problems under deterministic demand (Santos et al., 2022) While one might expect that reducing the MLOR level could increase waste on the retail side due to fewer fresh products being received, this is not necessarily the case (Mohamadi et al., 2023). Infact, the producer may also not have many old products in stock to be delivered to the retailer because it optimizes the production quantity in each period based on the available inventory. Additionally, for short shelf-life products, a one-period difference does not significantly affect product freshness, as shown by Santos et al. (2022) Ultimately, the retailer-to-consumer discount proposed in this thesis can potentially further help reduce outdated products at the retailer.

Figure 8 indicates that the implementation of the flexible rule in a centralized model prevents food surplus at the producer. In contrast, surplus increases in the retailer-Stackelberg scenario with a fixed MLOR level. Economically, surplus negatively impacts the producer's profit, since the salvage value of products sold through alternative channels is typically lower than their production cost. Consequently, an increase in surplus food is expected to decrease the total profit of the supply chain. From a sustainability standpoint, surplus food indicates that it may not be suitable for human consumption, thereby diminishing its value, akin to a situation of downcycling.

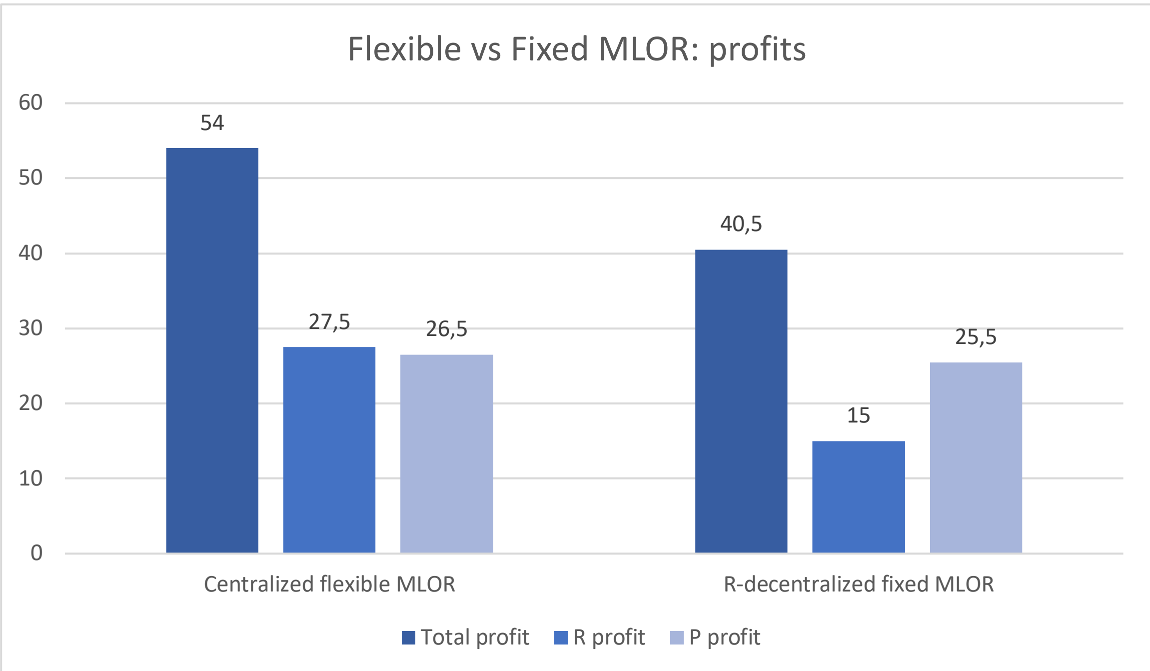

Figure 7. Comparison of flexible and fixed MLOR rule: profits

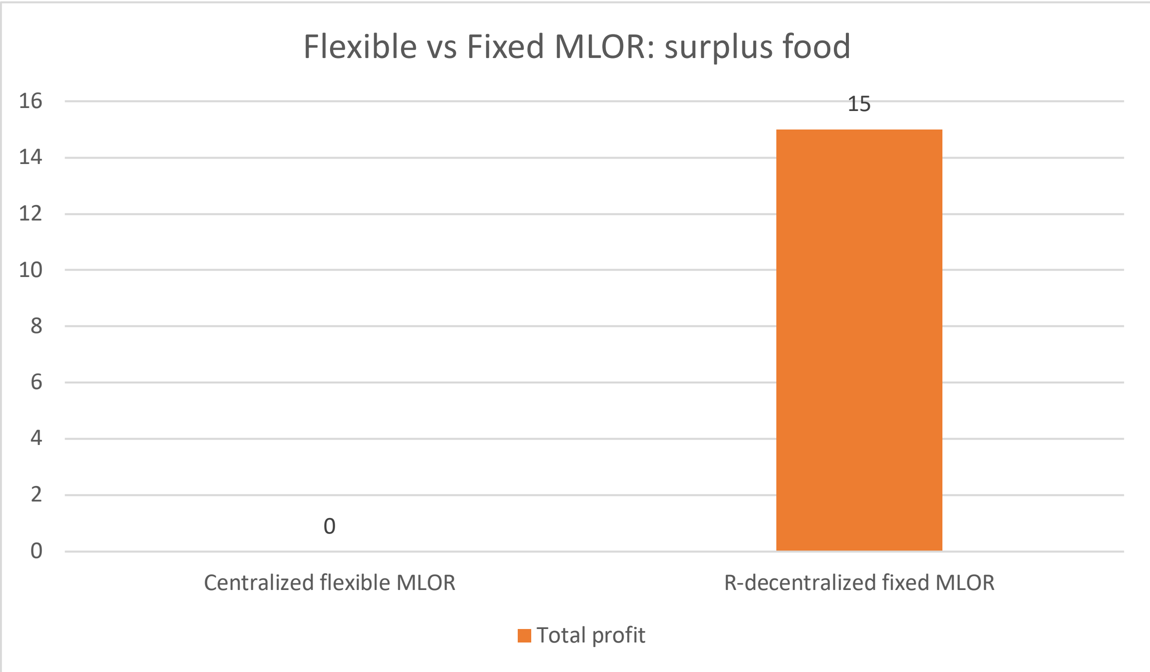

Figure 8. Comparison of flexible and fixed MLOR rule: surplus food

4.8 Comparison of centralized and decentralized models

This section highlights the main differences in outcomes between the centralized and retailer's decentralized optimization models, as illustrated in Figure 9 and Figure 10. Results show that the producer's profit increases in the centralized models (scenarios A and B) and the producer's decentralized model (scenario E), while the retailer's profit decreases, consistent with the objective functions defined in these models. Comparing flexible and fixed MLOR rules in both centralized and retailer's decentralized optimization the producer seems to benefit more from a fixed rule (scenarios B and D), whereas the retailer consistently benefits from a flexible rule (scenarios A and C). These findings align with the research by Santos et al. (2022). However, scenario E results show that the producer would adopt a flexible MLOR rule if it holds the most bargaining power.

As previously discussed, only scenarios A and D are achievable in the current supply chain, since implementing a flexible MLOR rule with a discount strategy requires both actors to agree and benefit from it. This necessitates collaboration, as the disadvantaged party would otherwise act differently, shifting the Stackelberg equilibrium. For instance, scenario B is not achievable because the retailer's profit is too low, reducing its incentive to collaborate. Similarly, scenario C is unfeasible because a selfish retailer would lead to very low producer profits, making the producer unwilling to implement the flexible rule and offer discounts. Scenario E is also unlikely, given the retailer's dominant bargaining power in current market conditions. Therefore, when comparing feasible scenarios (A and D), both actors may prefer to implement the flexible MLOR agreement collaboratively rather than the fixed rule in the retailer-Stackelberg scenario.

In the centralized models, the producer supplies more products to the retailer than needed to meet single-period demand, reducing inventory holding costs. Simultaneously, the retailer reduces fixed ordering costs, as daily orders are no longer necessary.

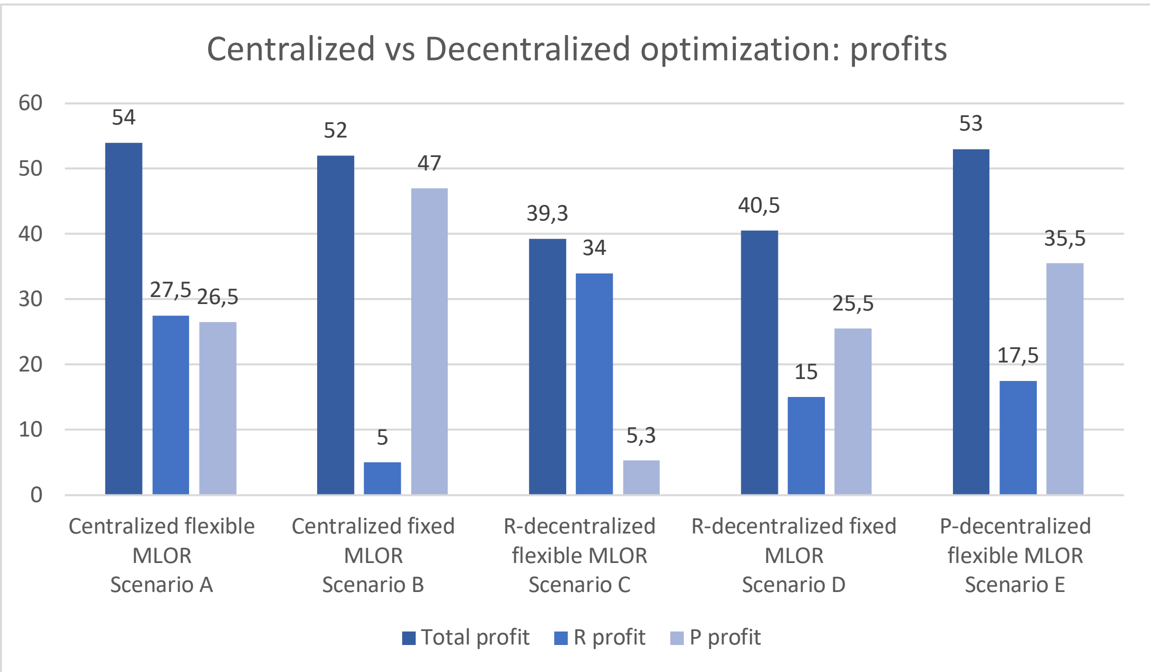

Figure 9. Comparison of centralized and decentralized optimization: profits

Food surplus is avoided when the objective function includes the producer's profit, thereby decreasing the producer’s costs. These cost reductions enhance the overall profitability of the supply chain in centralized models, making them outperform the decentralized models.

In scenarios C and D, surplus generation is expected, as the retailer does not consider it in its food waste calculations. Unexpectedly, surplus is also generated in scenario E, where it represents a loss for the producer. This suggests that collaboration is more effective in reducing food surplus than the flexible MLOR rule alone. However, flexibility is needed to foster collaboration, thereby indirectly contributing to the reduction of surplus food.

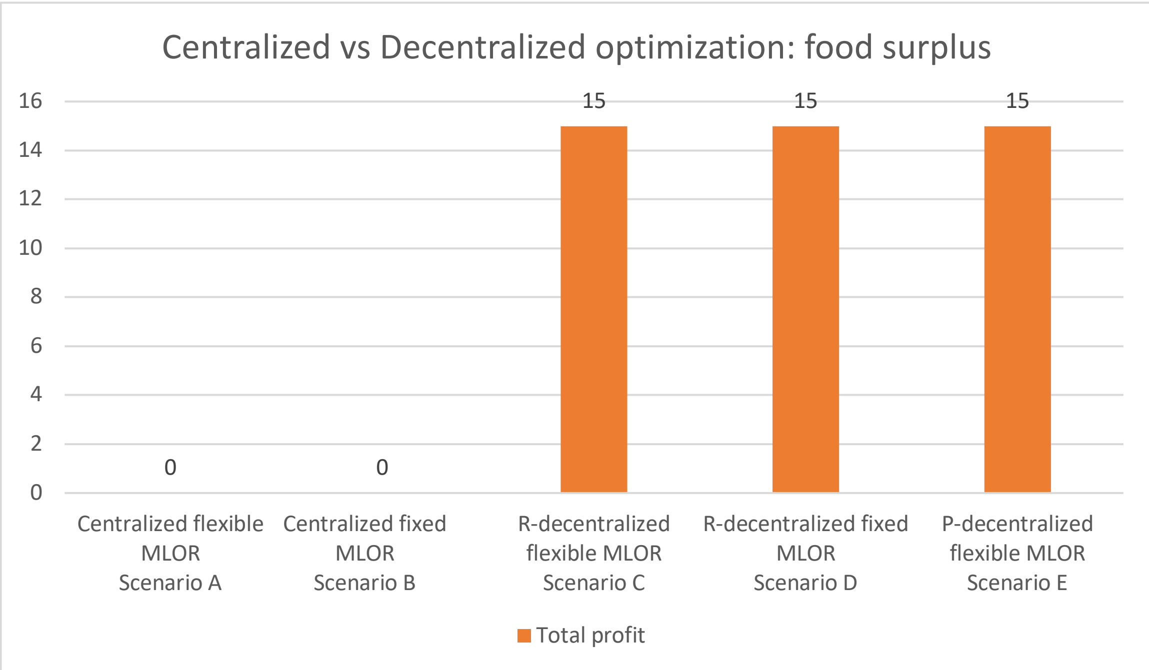

Figure 10. Comparison of centralized and decentralized optimization: surplus food

4.9 Comparison of producer and retailer benefits

Table 21 displays the contractual policies and discount strategies derived from optimizing the three proposed models allowing a flexible MLOR rule. As previous discussed, in scenarios B and D, the fixed MLOR is enforced in the model for comparison purpose, while in other scenarios (A, C, and E) the MLOR rule is a decision variable, optimized by the model. All scenarios (centralized, retailer's decentralized, and producer's decentralized) yield a flexible MLOR rule as output, with different discount strategies for each model. This indicates that both the retailer and the supplier benefit from this agreement in both the collaborative model, which aims to maximize overall supply chain profits, and the decentralized models, which focus on maximizing individual profits.

The findings reveal that the retailer does not benefit from collaborating with the producer in scenarios A and B but consistently benefits from relaxing the MLOR value. However, collaboration is essential for the retailer to fully realize the advantages of the flexible MLOR and the implementation of the discount strategy.

Conversely, the producer benefits more from collaboration than from optimizing its production process in the retailer-decentralized problem but may not benefit from the flexible MLOR rule in certain scenarios. These findings on collaboration are not surprising, as the retailer loses some of its bargaining power through collaboration, while the producer gains some.

Key insights arise regarding the flexibility factor: it is advantageous for the retailer, while the producer faces a trade-off. The producer must decide between implementing the discount strategy and adopting the flexible MLOR rule as the contractual policy in the centralized model or adhering to the fixed rule in the retailer's decentralized model.

Optimization model	**Contractual policy (decision variable)**	**Discount strategy (decision variable)**
Centralized	*Flexible MLOR rule*	*Discount in period 2*
Retailer's decentralized	*Flexible MLOR rule*	*Discount in period 2 and 3*
Producer's decentralized	*Flexible MLOR rule*	*Discount in period 3*

Table 21. Contractual policies and discount strategies resulting from the optimization of the proposed models

Figure 9 shows that the centralized model employing the flexible MLOR rule (scenario A) maximizes total profit, ensuring balanced individual profits for both the supplier and the retailer. Surprisingly, the powerful retailer achieves lower profits in all other scenarios, except for the retailer's decentralized model with a flexible MLOR (scenario D), which is unachievable because the retailer cannot implement the proposed strategy if it is not also beneficial for the producer.

Similarly, the producer attains higher profits in the producer's decentralized model with a flexible MLOR and in the centralized model with a fixed MLOR (scenarios B and D), which are unlikely to occur since they yield low profits for the retailer, who holds the most bargaining power. Excluding scenarios B and D, the most profitable scenario for the producer is also scenario A.

The reduction of food surplus at the producer appears to be more closely linked to retailer-producer integration than to the MLOR rule alone. Nevertheless, the proposed model can facilitate collaboration among stakeholders, indirectly aiding in reducing food surplus. This enhances the value of the centralized model (scenario A), which goes beyond profit maximization to include surplus reduction. It achieves a win-win situation by maximizing profits, minimizing food surplus, and distributing profits along the supply chain, resulting in balanced benefits for both actors.

5. CONCLUSIONS

Sustainability is a major concern in managing perishable food supply chains. Significant food waste occurs at the supplier-retailer interface due to existing policies and lack of collaboration among supply chain actors. Despite this, few studies address waste generated at this stage, and even fewer consider contractual policies as leverage points.

This thesis investigates the impact of a flexible MLOR rule on PFSC performance, focusing on two primary research questions: (1) how can retailers transition from a fixed to a flexible MLOR rule? (2) What are the potential benefits associated with adopting a flexible MLOR rule?

The main hypothesis is that optimizing the MLOR rule with a discount strategy benefits the food supply chain in terms of profits and waste reduction. The study examines the effect of reducing the MLOR agreement by one day of shelf life while implementing a producer-to-retailer discount to encourage acceptance of the reduced MLOR, and a retailer-to-consumer discount to prevent waste at the retail level. A Stackelberg game representing the interaction between the retailer leader and supplier follower in this innovative scenario is developed, along with a two-echelon model representing the integrated retailer-producer problem, with the discount as a decision variable. This model is then compared to the traditional setting where the MLOR is fixed by the retailer.

Findings indicate that implementing the discount strategy allows for a more relaxed MLOR level, increases overall supply chain profitability, and significantly reduces waste. Collaboration between the producer and retailer in setting the MLOR rule can completely eliminate waste at the manufacturer's end.

These results align with studies by Santos et al. (2022) and Mohamadi et al. (2023), which highlight the benefits of a flexible MLOR rule and its negligible impact on product freshness and retailer waste. The finding that a flexible MLOR policy with a discount strategy can improve profitability for both parties and serve as a collaboration mechanism suggests that the fixed MLOR rule's perceived benefits for retailers may be overrated.

Another key finding is that all three models (centralized, retailer’s decentralized, and producer’s decentralized) automatically select the flexible MLOR over the fixed one to optimize the objective function, if allowed. This highly recommends that practitioners reconsider their contractual policies and explore the implementation of the new collaborative interaction employing the flexible MLOR rule.

From a managerial perspective, focusing solely on reducing waste in retail stores may not effectively reduce waste across the entire supply chain. Such policies incentivize retailers to set higher MLOR levels to protect their profit, reduce their waste, and ensure consumer satisfaction, which has a counterproductive effect on the whole supply chain. Implementing flexible MLOR rules can reduce operational costs for producers, lower purchasing costs for retailers, and decrease prices for consumers, fostering a more efficient and sustainable supply chain. Innovative contracting approaches may thus enhance both economic and environmental performance across the food supply chain.

This thesis explores the effects of the newly proposed interaction between the retailer and the producer, though with several limitations. The model was investigated with a limited and fixed shelf life of three days, a time horizon of three days, and under deterministic demand. Future research could assess the effects of different shelf lives, longer time horizons, and uncertain demand. Sensitivity analysis on the discount percentages from producer to retailer and from retailer to consumer, as well as on production lot size, could also be performed.

It would be valuable to determine the discount percentage that maximizes supply chain profit when demand is age- and price-dependent, and to investigate the impact of a flexible MLOR rule on the producer when its lot size exceeds the demand of a single period. Other potential topics for future research include: (1) implementing a producer-to-retailer discount only on non-compliant units; (2) assessing the effects of the retailer-to-consumer discount on retailer’s waste to determine if it effectively reduces waste at the retailer level.

Another possible direction for future research is to develop the supplier-retailer interaction using a bilevel optimization model. This approach could be more suitable for representing the current market scenario, where the retailer is the leader aiming to maximize its profit while being constrained by the producer’s profitability. This pioneering study can serve as a foundation for these suggested future research directions.

Appendix A. Value of parameters

The table below displays the parameter values used in the model. Indexed parameters have different values for each index, ranging from 0 to 3.

The values for time horizon, demand, retailer discount percentage, consumer discount percentage, and lot size are chosen arbitrarily. The values for the other parameters are sourced from the work of Santos et al. (2022).

Nomenclature	Value	Source
c	2	Santos et al. (2022)
d_t	[0, 10, 10, 10]	Assumption developed in this work
f	5	Santos et al. (2022)
h	0.1	Santos et al. (2022)
h’	0.5	Santos et al. (2022)
l	15	Santos et al. (2022)
M	200	Santos et al. (2022)
MLOR	2/3	Santos et al. (2022)
o	1	Santos et al. (2022)
p_a	[0, 4, 3, 3]	Assumption developed in this work
r_a	[0, 5, 4.5, 4]	Assumption developed in this work
s	1	Santos et al. (2022)
sl	3	Santos et al. (2022)
u	5	Santos et al. (2022)
T	3	Assumption developed in this work

Appendix B. Producer's decentralized optimization model constraints

(2) - (13)

$$Q_t = d_{t+1} - IR_t \qquad \forall\ t \in T, t < T \qquad (14)$$

(15) – (33)

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