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Boosting Sales and Customer Welfare from Premade Foods (Let the Freshest Chicken Fly off the Shelf First)

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Abstract. This paper examines a grocery retailer's management of a premade food product. The retailer's goal is to maximize a weighted sum of direct profit and customer welfare. Multiple items of the product are produced in batches and immediately displayed for sale. Considering that each item's quality decreases while it sits on the shelf, the retailer chooses the shelf life, whether to issue items in first-in-first-out (FIFO) or last-in-first-out (LIFO) order, whether to timestamp items, and how to price items. In a base model, we find that the retailer should use LIFO issuance and *not* timestamp items. The intuition is that this increases customer welfare and allows for a longer shelf life, increasing sales and thus reducing waste. By extending the model, we identify features that can make FIFO optimal (such as a holding cost, upper bound on the shelf life, age-dependent disposal cost, or customer risk or loss aversion), and we show how customer heterogeneity can favor timestamps. Lastly, we show how a mandate to donate unsold food items (as implemented in France and California) can motivate a retailer to increase the shelf life, thereby reducing the quality and quantity of donated items.

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1. Introduction

The management of premade food is of prime importance for grocery retailers, customers, and sustainability. Premade food refers to rotisserie chicken, sushi, pizza slices and other fresh-baked goods, to-go salads, and other fresh food prepared in store. For customers, a top criterion for choosing a supermarket is the quality/freshness of its premade food (Oliver Wyman 2019, Browne 2021). For grocery retailers, effective management of premade food is crucial to attract customers and to generate profit, as premade food has been the fastest-growing category for a decade, and the COVID pandemic motivated the reconfiguration of many stores to allocate more space to production and display of premade food (Food Marketing Institute 2016, Browne 2021). The problem is that the quality of premade food degrades quickly, so its shelf life (the time elapsed from when the food is prepared until it is disposed of, if unsold) must be short, and a lot of it goes to waste. A multinational retailer famous for operational efficiency (hereafter called our motivational example retailer "MER" for brevity and anonymity) sought our advice to improve premade food management because they were throwing away 9% of premade food items, a higher rate than in any other food category. Wasted food is a major contributor to climate change[1] that could be redirected to feed the hungry.[2] Rotisserie chicken, the predominant premade food for MER and many other retailers, has been associated with animal cruelty, antibiotics resistance, plastic waste, water pollution, and harm to wildlife, in addition to climate change (Gerber et al. 2007, Kristof 2021, USDA 2021, Pyzyk 2024).

Management of premade food requires three key decisions: shelf life, issuance order, and whether to "timestamp," that is, indicate for customers the time at which food was prepared. Consider the illustrative example of these decisions for rotisserie chicken. MER's stores operate rotisserie chicken ovens at full capacity during open hours and use first-in-first-out (FIFO) issuance: When a batch of chickens comes out of the oven, they are shelved underneath the chickens that were already on the shelf to induce customers to take the chicken that has been on the shelf longest. MER does not timestamp for customers. MER's labels enable only employees (*not* customers) to distinguish how long a chicken has been on the shelf. An employee disposes of any chicken that has been on the shelf for *four hours*. In contrast, Costco uses a shorter shelf life of *two hours* for its famously juicy $4.99 rotisserie chicken that attracts customers to pay the annual membership fee, shop frequently, and walk all the way to the back of the store where the chickens are located, picking up additional products en route (Gasparro 2018, Hanbury 2018). In a reversal of its traditional practice, Costco started in 2024 to timestamp its rotisserie chickens, adding a visible sticker atop each chicken with the time when it came out of the oven, which enables shoppers to infer how fresh and juicy each chicken is. Sprouts Farmers Market also visibly timestamps its rotisserie chickens (Figure 1).

This paper studies a retailer's optimization of the shelf life, issuance order, price, and whether to timestamp items, in a model with the following key features. First, the retailer's objective is the retailer's direct profit from the premade food product plus the retailer's value associated with customers' welfare from the product. (Think of how customers' appreciation for Costco's juicy chicken generates value for Costco, through membership fees and boosted sales of other products.) Second, we allow for a general stochastic point process and batch size to represent capacitated food production in the store, for example, the process of batches of chicken coming out of the rotisserie oven. Third, an item's quality decreases as a linear or convex function of its wait time on the shelf. Fourth, an item's quality at the time that a customer arrives determines the customer's utility from purchasing the item and thus the retailer's sales. With timestamps, customers observe an item's freshness/quality and will not purchase an item that has waited too long on the shelf. Without timestamps, we focus on rational equilibria in which customers only purchase items if, on average, they derive positive utility from doing so; that imposes an upper bound on the shelf life, above which the retailer would have zero sales. Initially, in our base model formulation, customers are homogeneous and variable holding costs are negligible.

Our first main result is that *last-in-first-out (LIFO) issuance is optimal*. This result surprised us because FIFO is known to maximize sales and minimize waste (Nahmias 2011, p. 3), although only with a *fixed* shelf life. In contrast, we find that LIFO is optimal if the shelf life is optimally chosen. The rationale is that using LIFO rather than FIFO improves the quality of items purchased, and that enables a retailer to increase the shelf life and thereby increase sales and reduce waste. LIFO is optimal irrespective of the retailer's focus on direct profit or customer welfare.

Our second main result is that a retailer should *not* timestamp items. Timestamps increase waste and reduce sales by, in effect, reducing the shelf life. Even if timestamps enable optimal age-dependent pricing (price reduction as an item's quality degrades with time on the shelf), the retailer's objective is higher with a uniform price and no timestamps.

By extending our model formulation, we identify features that can make FIFO optimal (a holding cost, upper bound on the shelf life, age-dependent disposal cost, customer risk or loss aversion, or a *requirement* to visibly timestamp items). In those model extensions, to *not* timestamp remains optimal for the retailer.

We incorporate heterogeneity in customers' utility from the premade food and show how this can favor use of timestamps. Timestamps improve the allocation of items to those customers who value them most, which increases customer welfare. Moreover, timestamps can also increase sales by enabling a retailer who implements LIFO to extend the shelf life and sell to a wider range of customer types. With heterogeneous customers, we prove that LIFO remains optimal without timestamps and our numerical experiments

Figure 1. (Color online) Sprouts' Timestamped Rotisserie Chickens

indicate that LIFO is optimal whenever timestamps are optimal.

We develop insights for policy makers. New laws in France and California require retailers to donate unsold food or pay a fine. Such laws increase the disposal cost for unsold food, either by the fine or by the incremental cost of packing, cooling, and transporting the food for donation rather than using the prior disposal method. We show how this motivates retailers to increase the shelf life of food items, which reduces the quantity and quality of donated items. Our analysis helps explain two pernicious, unintended consequences documented by the French Ministry of Agriculture: (1) reduced quantity of food donated per store and (2) increased age of donated food, which causes donated food to go to waste, as "with a shorter and shorter [remaining time to expiration], the vast majority of less than 48 hours, … the food is sometimes not redistributable by the associations [the organizations that take food donations], which can lead to a transfer of waste from retailers to the associations and therefore to the communities" (Ernst and Young 2019, pp. 8–9).

2. Review of Related Literature

The perishable inventory literature widely assumes FIFO issuance (Nahmias 2011, p. 3) because, as shown in Pierskalla and Roach (1972), FIFO maximizes sales and minimizes backorders/lost sales and the number of items that expire. However, that literature also identifies several reasons why FIFO issuance may not be optimal. Tax considerations can favor LIFO over FIFO (Cohen and Pekelman 1979). With heterogeneous customers, non-FIFO issuance can be necessary to attract the most freshness-sensitive customers (Pierskalla and Roach 1972). If the length of time an item is useful in the field is a decreasing, convex function of the time it sits in inventory, LIFO issuance would make the items last longer on average in the field than does FIFO, and LIFO would have more items expire in inventory rather than in the field (Greenwood 1955). Relatedly, Akkaş and Honhon (2021) show that FIFO is suboptimal in a setting wherein the cost of expiration before the sale (e.g., in the supplier) is lower than the cost of expiration after the sale (e.g., in the retailer). This paper identifies a novel mechanism by which LIFO outperforms FIFO issuance: LIFO increases the average quality of purchased items, which enables the retailer to increase the shelf life and thus increase sales.

Assuming a fixed shelf life, Parlar et al. (2011) and Chen et al. (2014) show that inventory levels are lower under LIFO than FIFO so, with a sufficiently high inventory holding cost, LIFO outperforms FIFO. Based on those papers, one may conjecture that holding costs would also favor LIFO in our setting, particularly given our main result that LIFO dominates FIFO with zero holding costs. In contrast, we find that holding cost can favor FIFO! This counterintuitive result arises from the ability to adjust the shelf life: Because LIFO enables the retailer to increase the shelf life more than FIFO, it can actually result in *higher* inventory levels and associated holding costs.

Our model of equilibrium demand with no timestamps is adopted from the literature on unobserved queues with strategic customers (Hassin and Haviv 2003). In that literature, the wait time experienced by a customer varies with the (unobserved) queue length and customers choose whether to join the queue based on the average wait time. Similarly, in our model with no timestamps, the quality experienced by a customer varies with the (unobserved) time that the premade food item has waited on the shelf, and customers choose whether to purchase an item based on the average quality of purchased items.

Our model of food production in the store is inspired by the continuous-time queuing models of perishable and decaying inventory considered before in the literature; see the seminal papers by Graves (1982) and Kaspi and Perry (1983) and see Karaesmen et al. (2011) for a more extensive survey. We generalize this body of literature by allowing replenishments to occur in batches that arrive according to a general stochastic point process and by representing the equilibrium customer demand response to the retailer's policy.

The operations literature addresses grocery retailers' decisions with implications for food waste. These decisions include shelf space (Akkaş 2019), package sizing and pricing (Koenigsberg et al. 2010), ordering, allocation, and disposal with multiple demand classes (Abouee-Mehrizi et al. 2019, Chen et al. 2021), selling items loose versus in packages (Kirci et al. 2023), dynamic pricing under a food waste landfill ban (Sanders 2024), dynamic pricing while learning about demand and decay rates (Keskin et al. 2022), price discounting, shelf life, and display design for timestamped perishables (Atan et al. 2023), whether to dispose of excess food through donation or input to a premade food item (Lee and Tongarlak 2017), salesforce compensation (Akkaş and Sahoo 2020), transshipment between stores (Li et al. 2022), order quantity contingent on the age of items at the supplier's facility (Ferguson and Ketzenberg 2006), information sharing and coordination of order quantities between retailer and supplier (Ketzenberg and Ferguson 2008), store location (Belavina 2021), and payment models for an online grocery retailer (Belavina et al. 2017).

In modeling a specific decision by a retailer, the aforementioned papers and perishable inventory literature typically maximize the retailer's direct profit from the single product and not the effect of the decisions on customers' welfare and the retailers' profit from other products. In contrast, this paper follows Cachon (2014), Sumida et al. (2021), and Che and Tercieux (2021) in formulating a retailer's objective as maximizing a weighted sum of direct profit and customers' welfare. This is particularly important in modeling the management of premade food, because some grocery retailers deliberately sell a premade food item as a loss leader to attract shoppers (Hanbury 2018). The weight on customer welfare in the objective represents the retailer's value obtained indirectly by creating customer welfare through management of the single product under consideration.

Importantly for modeling customer welfare, related literature shows that food quality degrades continuously due to microbiological processes, temperature change that affects flavor and texture, loss of moisture, or decreased aesthetic appeal due to change in coloration (Potter and Hotchkiss 1995, Van Boekel 2008, Hammond et al. 2015). Moreover, Tsiros and Heilman (2005) experimentally demonstrate that a majority of customers perceive that the quality of grocery items decreases throughout the course of their shelf lives. Motivated by this literature, our paper allows for quality and associated customer welfare to decrease continuously while the premade food sits on the shelf.

A related literature shows how expiration date labeling of packaged food causes food waste by customers. The European Union (EU) requires packaged food to have either a "Best Before Date" or "Expiration Date" label. Buisman et al. (2019) and the literature surveyed therein show that food typically remains good to consume past that date and yet customers throw away food that passes the date, without checking. Similarly, although the U.S. government does *not* require or regulate date-labeling of food products, Tsiros and Heilman (2005) and Leib et al. (2013) observe that packaged foods commonly have a "Sell By Date" or similar label that customers confusedly interpret as the deadline for consuming or throwing away the item, causing them to throw away food that is still good. To reduce food waste, Leib et al. (2013) recommends that retailers eliminate "Sell By Date" type labels and provide only the expiration date beyond which consumption would be unsafe. Buisman et al. (2019) recommend that retailers dynamically update any expiration date, based on the record of temperatures at which the item has been maintained, to accurately predict the time at which the food will become unsafe. In contrast to this expiration date literature, we model a retailer's decision of whether to label food with the specific time at which it was *made*, which could convey information about an item's freshness/quality without prompting a customer to throw it away too soon.

Regarding quality disclosure, the seminal result is that competing firms voluntarily disclose the quality of their products (Grossman 1981, Milgrom 1981). Markopoulos and Hosanagar (2018), and papers surveyed therein, identify countervailing reasons a firm might *not* disclose information about quality. For example, to increase the long-run average rate at which customers choose to pay and wait for service, a firm should *not* disclose information about the current wait time if and only if the customer arrival rate is sufficiently low (Hassin 1986). With a low arrival rate, customers know that the long-run average wait time is short and so (with no information about the current wait time) every customer pays and waits for service: even at times when the current wait is so long that a customer would be better off balking. Our model is similar in that, if the retailer does not timestamp premade food items, customers choose whether to buy an item based only on the long-run average quality of purchased items, so customers may buy an item that has been on the shelf so long that, if it had a timestamp, they would not have bought it.

3. Base Model

The food product is made in the store in a batch process and immediately placed on the shelf for sale at price $p \geq 0$. The batch size is $B \in \mathbb{N}$ items. A new batch is placed on the shelf according to a stochastic point process with independent and identically distributed interarrival times $\{\ell_n\}_{n\in\mathbb{N}}$. In other words, ℓ_n denotes the time between the nth replenishment and the $(n+1)$th replenishment. We assume $\mathbb{E}[\ell_n]$ is finite and denote $\mu := \frac{1}{\mathbb{E}[\ell_n]}$. We also assume that the first batch arrives at time $t = 0$ and the shelf is empty prior to that.

The quality of an item decreases with its time on the shelf. An item has quality $q(0) > 0$ when first placed on the shelf. When the item has age $\tau \geq 0$, that is, has waited on the shelf for time τ, it has quality $q(\tau)$ that is weakly convex and strictly decreasing in τ. For mathematical and expositional convenience, we assume that $\lim_{\tau\to\infty} q(\tau) = -\infty$. A customer who purchases an item of age τ at price p gains utility $q(\tau) - p$.

The retailer chooses the price p, shelf life T, issuance rule I, and whether to timestamp items; we use π to succinctly represent the vector of those choices.

The shelf life $T \geq 0$ is the length of time for which an item is displayed on the shelf, if not sold to a customer. When an item's age τ reaches T, the item is removed from the shelf at disposal cost d to the retailer; d could be either positive or negative, with positive d representing a disposal cost and negative d representing a salvage value for unsold inventory.

The issuance rule I can be either FIFO (denoted by $I = F$) or LIFO (denoted by $I = L$). Let z_t^π denote the inventory level (number of items on the shelf) at time t and τ_t^π denote the age of the item on offer at time t when an item is in stock ($z_t^\pi > 0$). With FIFO issuance,

τ_t^π is the age of the oldest item on the shelf, whereas with LIFO issuance, τ_t^π is the age of the newest item.

Customers arrive at the shelf according to a Poisson process with rate λ and each customer purchases at most one item. Let t_i denote the time of the i-th customer arrival, and $N_c(t)$ denote the number of customer arrivals during time period $[0, t]$. A customer who arrives while no items are in stock leaves without purchasing an item. A customer who finds items in stock rationally decides whether to purchase one item at price p or obtain zero utility from no purchase; customers who are indifferent decide to purchase.

Sales depend on the retailer's policy π in the following manner. Zero sales occur with shelf life $T = 0$, so let us consider $T > 0$. If the retailer timestamps items, a customer can observe the age and quality of any item on offer and make a purchase decision accordingly. Therefore, with timestamps, a customer arriving at time t purchases an item if and only if $z_t^\pi > 0$ and the observed quality of the item on offer exceeds the price, $q(\tau_t^\pi) \geq p$, in which case the customer gains positive utility $q(\tau_t^\pi) - p \geq 0$. The retailer does not clutter the shelf with items too old to sell (items with age $\tau > q^{-1}(p)$), so with timestamps, shelf life T and price p must satisfy

$$q(T) \geq p. \tag{3.1}$$

With timestamps and (3.1), each arriving customer purchases an item if the shelf is not empty, and the average rate of sales is

$$S^\pi := \lim_{t\to\infty} \frac{1}{t} \sum_{i=1}^{N_c(t)} \mathbf{1}_{\{z_{t_i}^\pi > 0\}}, \tag{3.2}$$

which is strictly positive because $T > 0$.

Without timestamps, customers *cannot* observe an item's age and quality, so instead they base their purchase decision on the average quality of purchased items. Specifically, a customer arriving at time t purchases an item if and only if $z_t^\pi > 0$, and the resulting average quality of purchased items exceeds the price:

$$Q^\pi := \lim_{t\to\infty} \frac{1}{t} \sum_{i=1}^{N_c(t)} q(\tau_{t_i}^\pi) \mathbf{1}_{\{z_{t_i}^\pi > 0\}} / S^\pi \geq p. \tag{3.3}$$

Notice that Q^π is the average quality of purchased items, in the case that each arriving customer purchases an item if the shelf is not empty. With no timestamps, the price p, issuance rule I, and shelf life $T > 0$ must satisfy (3.3) or no customer would purchase an item on offer. In other words, we restrict attention to pure strategy rational equilibria in which an arriving customer that finds an item on offer purchases it if the retailer's policy π satisfies (3.3); otherwise, the retailer has zero sales.

In summary, to have zero sales ($S^\pi = 0$), the retailer can set shelf life $T = 0$, whereas to have strictly positive sales ($S^\pi > 0$), the retailer is constrained to use a policy π with a price p, issuance rule I, and shelf life $T > 0$ that satisfy (3.1) when items are timestamped or (3.3) when items are not timestamped, respectively.

The premade food product generates utility for customers at average rate

$$W^\pi := (Q^\pi - p)S^\pi,$$

which we refer to as "customer welfare," and is disposed of at average rate

$$D^\pi := \mu B - S^\pi.$$

The retailer's objective is to maximize

$$pS^\pi - dD^\pi + fW^\pi. \tag{3.4}$$

Here, $pS^\pi - dD^\pi$ represents the retailer's direct profit from selling the premade food product to customers and disposing of any leftovers, and $f \in [0, 1]$ is the value that the retailer assigns to the customer welfare. The case $f = 0$ represents a retailer that focuses solely on the direct profit. Larger f could represent a retailer that indirectly profits from generating welfare for customers with the premade food product, for example, from sales of other products who come to the store for the premade food product or by charging a higher membership fee to shop in the store. In the case $f = 1$, the objective is to maximize the social welfare generated by the premade food product.

We focus on the interesting parameter region in which the retailer optimally sets a shelf life $T > 0$. To that end, we assume $q(0) > -d$, meaning that the value of a fresh-made item to a customer exceeds any salvage value; otherwise, the retailer simply should dispose of all items. When we consider an exogenously fixed price p, we assume that that price exceeds any salvage value, $p > -d$, and is low enough to generate sales, $p < q(0)$. However, when we optimize the price p, we consider all candidate prices $p \geq 0$.

Several aspects of our model formulation warrant further discussion.

3.1. Negligible Variable Holding Cost

The retailer's objective (3.4) does not consider any cost of holding inventory on the shelf. Inventory of premade food has negligible variable capital holding cost, because it is held only for a few hours due to its rapid quality degradation. The main cost of holding inventory of premade food is a sunk *fixed* cost of allocating a space to hold and display the premade food (like the rotisserie chicken display shelf in Figure 1). We implicitly assume that the space is adequate to hold the inventory of items. Section 5.3 discusses how a variable holding cost could change our results.

3.2. Customer Purchasing Behavior with No Timestamps

Without timestamps, customers can learn about the quality of a retailer's premade food products by reading reviews on Reddit, Yelp, Quora, or the grocery retailer's website or by regularly purchasing the product. For instance, consider the following illustrative quotes on Reddit[3] regarding rotisserie chicken: "I buy the Costco rotisserie chicken all the time," "I end up buying 2-3 a week," "Best weekly purchase I make." Customers continue to purchase a product despite some disappointments, as illustrated by the quote "Usually it's pretty good, but sometimes it's so overcooked that the wings are cardboard consistency. It's worth the gamble."[4]

In the literature on unobserved queues, an arriving customer decides whether to participate based on the *average* wait time (Hassin and Haviv 2003). Similarly, we assume that, without timestamps, an arriving customer decides whether to purchase an item based on the *average* quality of purchased items.

Without timestamps, in our base model with homogeneous customers, we focus on pure strategy rational equilibria in which *all* customers who find an item on offer purchase it, if average quality exceeds the price as expressed in (3.3). In doing so, we assume that a retailer can induce a Pareto dominant equilibrium (equilibrium with highest sales, objective value and customer welfare) in case other equilibria exist. Section EC.8 of the Online Appendix proves that our focal equilibria are Pareto dominant, though other rational equilibria may exist with *only a fraction* of customers purchasing the item on offer. Section EC.8 of the Online Appendix also explains practical ways in which a retailer can ensure that such a Pareto dominant equilibrium (with higher sales) occurs. If the price p is sufficiently close to zero, a customer may in some instances purchase an item of negative quality (e.g., the aforementioned chicken so overcooked as to be of cardboard consistency) while average purchased quality exceeds the price.

3.3. Quality Degradation

Imagine biting into a fresh-baked baguette (or chocolate croissant) hot out of the oven. By the laws of physics, a hotter item loses its heat and moisture faster, so those fresh-baked qualities of your baguette decrease as a convex function of time out of the oven. In models based on physics and chemical kinetics in the food science literature, the quality of a food product is a strictly decreasing convex function of its age (Van Boekel 2008, Hammond et al. 2015). Tsiros and Heilman (2005) provide empirical evidence that customers' willingness-to-pay for a food product is a strictly decreasing function of its age; for a dairy or vegetable product, the function is linear, whereas for a meat product, the function is strictly convex. Therefore, in our model, quality is a strictly decreasing convex function of age.

All our analytical results, including the dominance of LIFO over FIFO with no timestamps, hold when quality is a linear function of age and are driven (to first-order) by the quality of the items degrading on the shelf and LIFO's ability to extend shelf lives because it issues higher-quality items to customers.

However, strict convexity in quality as a function of age, as in the baguette example, increases the advantage of LIFO over FIFO, because LIFO enables customers to obtain an item hot out of the oven, whereas cooler items, having strictly lower rate of quality degradation, wait on the shelf. Conversely, if quality was a strictly concave function of age, LIFO would have less advantage and FIFO could possibly be optimal; see Section 5.4 for numerical examples.

In comparative statics, we say that food with quality schedule $q'(\tau)$ "degrades faster" than food with schedule $q(\tau)$ if $q(0) = q'(0)$ and $q(\tau) - q'(\tau)$ increases with τ.

3.4. Replenishment Process

Taking the food production process (i.e., the batch size B and distribution of batch interarrival times ℓ_n) as given, while focusing on the choice of issuance rule, shelf life, whether to timestamp items, and price, is especially motivated by the example of rotisserie chicken, the predominant premade food product for MER and many other grocery retailers. Production requires that space within the store must be allocated and equipped, particularly through installation of the rotisserie oven(s). In a typical MER store, the rotisserie chicken oven operates at full capacity, producing a fixed number of chickens at intervals of approximately one hour; there is no idle, reserved capacity that could be activated dynamically to refill an empty shelf. The size of the oven (batch size) or the cooking time (interarrival time between batches) would only very rarely be modified. Similarly, in our local Walmart and in bakeries throughout Europe, fresh baguettes are baked and replenished in batches on the shelf at regular intervals, throughout open hours.

Our main results hold in a model extension in which the retailer optimizes the batch size B and production rate μ. Proofs are provided in Section EC.9 of the Online Appendix.

3.5. Issuance

Without timestamps, the retailer could implement either LIFO or FIFO issuance with a shelf design that induces customers to pick from the top (or from the front) and having employees place items on the shelf in the desired issuance order. Without timestamps, items appear identical to customers, so customers presumably will take the accessible item rather than exert effort to dig for an identical item. Stores commonly use stickers or tags that allow employees, but *not* customers, to order items by relative age.

With timestamps, a retailer could implement LIFO by promoting the preferred newest item or enabling customers to pick their preferred item, as with Sprouts' display in Figure 1. A retailer must work harder to implement FIFO with timestamps to keep customers from picking their preferred item. A retailer could implement a desired issuance order by having employees hand out items to customers in that order, as is done in many bakeries.

Therefore, we assume the retailer can choose to implement either FIFO or LIFO issuance. Our main results hold with imperfect implementation of the chosen issuance; see Section EC.10 in the Online Appendix.

4. Results for Base Model

Our results are organized as follows. Section 4.1 characterizes the retailer's optimal choice of issuance rule, shelf life, and price, assuming no timestamps. Section 4.2 characterizes the retailer's optimal choice of issuance rule, shelf life, and price under a requirement to timestamp items and concludes that timestamps reduce the retailer's objective. Lastly, Section 4.3 develops insight for regulators that aim to reduce food or plastic waste.

All figures in this section and the next (Section 5) illustrate results for a running example with exogenously fixed price $p = 1$, customer arrival rate $\lambda = 1$, Poisson replenishment with rate $\mu = 1$ and batch size $B = 1$, and quality $q(\tau) = 2 - 0.5\tau$.

In the statements of results, we use "increasing" and "decreasing" in a weak sense, and we explicitly indicate comparisons that hold in the strict sense (e.g., "strictly increasing").

For brevity, we refer to S^π, D^π, W^π, and Q^π as *sales*, *disposals*, *customer welfare*, and *purchased quality*, respectively. These quantities depend on the retailer's policy π. However, for initial analyses in which some of the decisions (such as the price p) are fixed, we will highlight the dependency on decisions that vary.

For the analysis, it helps to remember that customer welfare is $W^\pi = (Q^\pi - p)S^\pi$ and note that the objective (3.4) can be rewritten equivalently as

$$[(1 - f)p + d]S^\pi + fS^\pi Q^\pi - dB\mu. \qquad (4.1)$$

4.1. With No Timestamp

We first discuss the case when the price is fixed exogenously. This simplifies the exposition and is relevant for some retailers such as Costco, which has had a fixed low price for rotisserie chickens and for hot dogs for nearly two decades.

Recall that to have any sales without timestamps, the retailer must choose the issuance rule I and shelf life T to ensure that the (long run average) purchased quality $Q^{I,T}$ exceeds the price p, as represented by Constraint (3.3). Our first result considers a fixed issuance I and characterizes how the purchased quality $Q^{I,T}$ and sales $S^{I,T}$ depend on the shelf life T, proving that Constraint (3.3) is equivalent to an upper bound on T.

Lemma 1. *Under any issuance $I \in \{F, L\}$, purchased quality $Q^{I,T}$ is continuous and strictly decreasing and sales $S^{I,T}$ are continuous and strictly increasing in the shelf life T for $T \in (0, \overline{T}_I]$, where*

$$\overline{T}_I := \max\{T \geq 0 : Q^{I,T} \geq p\}. \qquad (4.2)$$

Moreover, Constraint (3.3) is satisfied if and only if $T \in (0, \overline{T}_I]$.

For any issuance and assuming that customers who find items in stock purchase one, increasing the shelf life will increase sales, by allowing more customers to find items in stock. However, the additional sales will be of items of lower quality that would otherwise have been disposed, so the average quality of items purchased will decrease. The $\overline{T}_I$ is the maximum shelf life at which, rationally, customers that find items in stock make a purchase. Therefore, the retailer has sales $S^{I,T} > 0$ if and only if $T \in (0, \overline{T}_I]$ and the choice of shelf life can be constrained to $T \in [0, \overline{T}_I]$ without incurring any loss in optimality.

Which issuance rule should the retailer use? Lemma 2 summarizes the tradeoffs between choosing FIFO versus LIFO under a fixed shelf life T.

Lemma 2. *For any fixed shelf life $T \leq \min(\overline{T}_F, \overline{T}_L)$, purchased quality is strictly lower and sales are strictly larger under FIFO than under LIFO: $Q^{F,T} < Q^{L,T}$ and $S^{F,T} > S^{L,T}$.*

Lemma 2 formalizes the intuition that with a fixed shelf life, FIFO induces customers to purchase older items first and thus conserves the newer items, which can remain longer on the shelf; in turn, this leads to more sales (and fewer stockouts and disposals) than LIFO. The tradeoff is that purchased quality is lower under FIFO than under LIFO.

An important implication of Lemmas 1 and 2 is that the maximum shelf life at which customers buy items is larger with LIFO than with FIFO, that is, $\overline{T}_L > \overline{T}_F$. LIFO yields strictly larger purchased quality than FIFO for any shelf life ($Q^{L,T} > Q^{F,T}$), so with LIFO, the retailer can increase the shelf life while ensuring that purchased quality exceeds the price. Later, we will use this critical observation in proving that LIFO is optimal if the retailer can jointly optimize the issuance and shelf life.

For any fixed shelf life that yields sales under either issuance, our next result compares FIFO and LIFO and proves that FIFO maximizes Objective (3.4) if the retailer places little weight on customer welfare f or if the disposal cost d is large.

Proposition 1. *Suppose that the retailer uses a fixed shelf life* $T \le \min(\overline{T}_F, \overline{T}_L) = \overline{T}_F$.

a. *There exists a threshold* $\overline{f} > 0$ *such that FIFO issuance is optimal if and only if the weight on customer welfare satisfies* $f \le \overline{f}$.

b. *The threshold* $\overline{f}$ *increases with the disposal cost d and satisfies* $\overline{f} = 1$ *for* $d \ge (Q^{L,T}S^{L,T} - Q^{F,T}S^{F,T})/(S^{F,T} - S^{L,T})$.

This follows from Lemma 2. Because FIFO maximizes sales for any given shelf life $T \le \overline{T}_F$, FIFO is optimal for a retailer that maximizes direct profit ($f = 0$). Moreover, increasing the disposal cost d favors FIFO and, when the disposal cost d is sufficiently large, FIFO is optimal for all $f \in [0, 1]$. On the other hand, because LIFO maximizes the purchased quality, LIFO may generate more customer welfare than FIFO. Then, increasing the weight f on customer welfare favors LIFO, as illustrated in Figure 2 for our running example.

Proposition 1 is consistent with known results in the literature on perishable inventory management with a *fixed* shelf life (Pierskalla and Roach 1972, Nahmias 2011) and is a useful benchmark for our next results on the *joint* choice of issuance and shelf life.

Regarding the optimal joint choice of issuance and shelf life, our results thus far raise an important question. Suppose $f = 0$, so the objective simplifies to maximizing sales. Lemmas 1 and 2 imply that with FIFO and the optimal choice of shelf life $\overline{T}_F$, sales would be strictly larger than with LIFO and that same shelf life $T = \overline{T}_F$. However, the optimal shelf life with LIFO would be the larger $\overline{T}_L$, which would yield larger sales than $\overline{T}_F$. Would LIFO with $\overline{T}_L$ yield greater sales than FIFO with $\overline{T}_F$?

A joint choice of issuance I and shelf life $T \in [0, \overline{T}_I]$ is equivalent to a joint choice of issuance I and sales $S \in [0, S^{I,\overline{T}_I}]$. This follows because sales $S^{I,T}$ are continuous and strictly increasing in the shelf life T for $T \le \overline{T}_I$ by Lemma 1, so there is a one-to-one relationship between any shelf life value $T \in [0, \overline{T}_I]$ and any sales value $S^{I,T} \in [0, S^{I,\overline{T}_I}]$.

In determining the optimal choice of issuance I and sales $S \in [0, S^{I,\overline{T}_I}]$, it helps to note that the retailer's objective (4.1) depends on issuance and sales only through S and $S \cdot Q^{I,T}$ (where T is the shelf life satisfying $S^{I,T} = S$), or equivalently, the objective depends only on the sales S and the corresponding customer welfare $W^I(S) := S \cdot (Q^{I,T} - p)$.

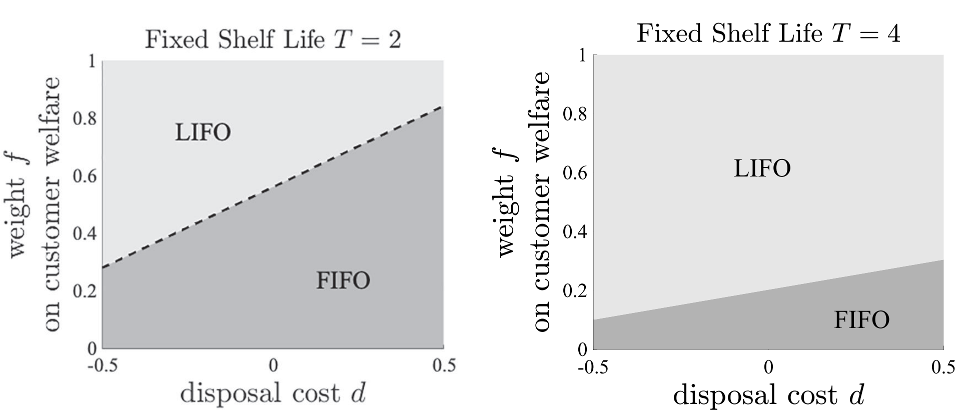
The next result provides the critical building block needed to prove that LIFO dominates FIFO by showing that LIFO achieves strictly larger maximal sales than FIFO and that for any sales level achieved by both, LIFO generates strictly larger customer welfare.

Lemma 3. *The maximal sales are strictly larger under LIFO than FIFO:* $S^{L,\overline{T}_L} > S^{F,\overline{T}_F}$. *LIFO delivers strictly higher customer welfare* $W^L(S) > W^F(S)$ *for any sales* $S \in (0, S^{F,\overline{T}_F}]$.

The main driver for this result is that an item's quality strictly decreases with time on the shelf. By providing a customer the highest-quality item available, LIFO increases customer welfare and enables the retailer to set a longer shelf life, thereby increasing sales. Strict convexity in the quality degradation schedule would introduce a second-order advantage for LIFO over FIFO, by letting customers enjoy fresh items while older items, with lower rates of quality decrease, remain on the shelf.

The proof of Lemma 3 is nontrivial and insightful in its own right, so we outline this below. Imagine implementing FIFO with shelf life $T_F \le \overline{T}_F$, which results in sales $S^{F,T_F} = S > 0$. It is not obvious that LIFO issuance can also achieve sales S, so the proof constructs two hypothetical policies, one based on FIFO and one based on LIFO issuance, that preserve key properties of the original systems and then compares these to arrive at the result. The first is a "forced-LIFO" policy with LIFO issuance and a sufficiently large shelf life $T_L > T_F$ to achieve sales S in a setting where all customers who find items in stock *are forced* to buy. With customers forced to buy, it is always possible to find such a T_L by suitably extending the shelf life; additionally, the

Figure 2. Optimal Issuance for a Fixed Shelf Life



expression for the purchased quality under this forced-LIFO policy would be *exactly* Q^{L,T_L} appearing in (3.3). To prove that customers would *willingly* buy items with LIFO and T_L, that is, that $Q^{L,T_L} \geq p$, it suffices to argue that customer welfare $S \cdot (Q^{L,T_L} - p)$ under forced-LIFO exceeds customer welfare under the original FIFO policy $S \cdot (Q^{F,T_F} - p)$ (which is positive because customers willingly buy under that policy). To do so, the proof introduces a "hidden-FIFO" policy, which sells items with age at most T_F to customers according to FIFO issuance but only discards items with age strictly above T_L (so items with age $T \in [T_F, T_L)$ are kept on the shelf, but "hidden" from customers). By construction, the hidden-FIFO policy would yield the same sales S and the same customer welfare $S \cdot (Q^{F,T_F} - p)$ as the original FIFO policy. The proof then argues (through an inductive, sample-path argument) that hidden-FIFO maintains a higher cumulative inventory of fresher items than forced-LIFO at any time; because both policies achieve the same sales S and the quality degradation is weakly convex in age, this implies that the customer welfare is higher under forced-LIFO than hidden-FIFO and completes the proof.

Theorem 1 characterizes the retailer's optimal issuance and shelf life.

Theorem 1. *The retailer's unique optimal policy is to use LIFO and shelf life*

$$T_L^* = \min\left(\overline{T}_L,\, q^{-1}\left(p - \frac{p+d}{f}\right)\right). \tag{4.3}$$

T_L^* *decreases with* f *and as quality degrades faster, and increases with* d.

A significant change occurs when the retailer jointly optimizes the issuance and shelf life. With a fixed shelf life, by Lemma 2, FIFO results in higher sales (and correspondingly fewer disposals) than LIFO. Joint optimization of the issuance and shelf life reverses that result. LIFO results in higher sales than FIFO. In our running example, the shift from FIFO to LIFO significantly increases the retailer's objective through a large increase in shelf life and, when f is not too small, an increase in customer welfare.[5] This highlights the importance for a retailer to jointly choose the issuance and shelf life.

Theorem 1 shows that as f increases, as quality degrades faster, and as the disposal cost d decreases, the retailer removes items from the shelf earlier. In the extreme case $f = 0$, a direct profit-maximizing retailer uses the largest shelf life $\overline{T}_L$ at which all customers purchase an item upon finding one in stock. At the opposite extreme $f = 1$, a social welfare-maximizing retailer uses shelf life $q^{-1}(-d)$ and disposes of an item precisely when its value to a customer falls to the salvage value (if $q^{-1}(-d) \leq \overline{T}_L$, so that doing so is feasible).

Whereas all the above results were derived for a fixed price p, the next proposition characterizes the optimal issuance rule I, shelf life T, and price $p \geq 0$ that maximize the retailer's objective in (3.4), with no timestamps. Here, $\overline{T}_L(0)$ denotes the value of $\overline{T}_L$ from (4.2) for $p = 0$, that is, $\overline{T}_I(0) = \max\{T \geq 0 : Q^{L,T} \geq 0\}$.

Proposition 2. *The unique optimal issuance is LIFO. The unique optimal shelf life is* $T_L^* := \min(\overline{T}_I(0), q^{-1}(-d))$. *The unique optimal price is* $p_L^* := Q^{L,T_L^*}$ *except in the case that* $f = 1$, *where any price in* $[\max(0, -d), p_L^*]$ *is optimal.*

That LIFO is optimal follows from our earlier results under any fixed price p. To arrive at the optimal shelf life and price, the proof of Proposition 2 recognizes that with $f = 1$ and under any shelf life T satisfying $Q^{L,T} \geq p \geq 0$, the retailer's objective is increasing in p so the retailer should set the highest price at which customers will purchase the product, $p = Q^{L,T}$. At that price, customers derive zero welfare and the retailer's objective is equivalent to (3.4) with $f = 1$ (social welfare), so the retailer should issue items in LIFO order and dispose of items precisely when their value to the customer falls to the salvage value $-d$, by setting $T = q^{-1}(-d)$. The optimal shelf life is then obtained by accounting for the constraint that the price should be positive, $p \geq 0$, which is equivalent to an upper bound on the shelf life of $\overline{T}_I(0)$. In the case that $f = 1$, any price in the interval $[\max(0, -d), Q^{L,T_L^*}]$ is optimal because the price only serves as an internal transfer from customers to the retailer, with no effect on the social welfare.

Notice that, although our optimization allows for the retailer to set any price $p \geq 0$, the optimal price satisfies $p_L^* < q(0)$ and, in the case $d < 0$, meaning that the item has a salvage value $-d > 0$, an optimal price satisfies $p_L^* > -d$. This confirms that in considering an exogenously fixed price with $p \in (-d, q(0))$ we do not rule out the optimal price p_L^*.

4.2. Timestamp Items?

Consistent with Section 4.1, we first consider the case with an exogenously fixed price p.

Recall that if the retailer timestamps the items, then an arriving customer can infer an item's age τ and quality $q(\tau)$. No customer would buy an item aged $\tau > q^{-1}(p)$ because doing so would generate strictly negative utility $q(\tau) - p < 0$. The retailer does not clutter the shelf with items that are too old to sell. Therefore, timestamps effectively constrain the retailer to set the shelf life short enough to meet Constraint (3.1), or equivalently,

$$T \leq q^{-1}(p). \tag{4.4}$$

Under this constraint and given any issuance I, all customers finding an item in stock purchase it and the resulting sales $S^{I,T}$, purchased quality $Q^{I,T}$, and objective value are given by (3.2), (3.3), and (3.4), respectively.

Indeed, with any issuance I and *feasible* shelf life T, the sales $S^{I,T}$, purchased quality $Q^{I,T}$, and Objective Value (3.4) are the same with timestamps as without timestamps. Our first result is that the choice of shelf life is more constrained with timestamps so, under our assumption that the retailer chooses the shelf life to maximize Objective (3.4), timestamps reduce the objective but benefit customers.

Proposition 3. *Under any issuance $I \in \{F, L\}$,*

a. *Timestamps strictly reduce the maximum shelf life to*

$$q^{-1}(p) < \overline{T}_I. \tag{4.5}$$

b. *Timestamps reduce the retailer's objective but increase customer welfare.*

The intuition for (4.5) is that the average quality of purchased items $Q^{I,T}$ is strictly greater than the worst-case quality at which items are disposed $q(T)$. At the maximum shelf life with timestamps, the worst-case quality satisfies $q(T) = p$. In contrast, Lemma 1 implies that at the maximum shelf life without timestamps $\overline{T}_I$, average quality $Q^{I,\overline{T}_I} = p$, and the worst case quality is strictly lower $q(\overline{T}_I) < p$.

Timestamps increase customer welfare because timestamps ensure that customers never experience negative ex post utility from purchasing items and because the retailer's optimal choice of shelf life with timestamps is not too low from customers' perspective.

In reality, a retailer might be inclined, or even required, to timestamp premade food items for reasons not represented in our base model. Therefore, in a setting with timestamps, we will characterize the retailer's optimal policy and whether the retailer can achieve the same objective value as without timestamps.

Because any feasible shelf life with timestamps satisfies $T < \min(\overline{T}_I, q^{-1}(p))$, all the results in Section 4.1 obtained for a shelf life $T \leq \overline{T}_I$ are relevant to this setting with timestamps. In particular, with any fixed issuance I, *decreasing* the shelf life T will strictly decrease sales $S^{I,T}$ and strictly increase purchased quality $Q^{I,T}$ (Lemma 1). For any fixed shelf life T, FIFO issuance generates strictly greater sales $S^{I,T}$ albeit strictly lower purchased quality $Q^{I,T}$ than LIFO issuance (Lemma 2), so FIFO issuance is optimal when the weight f on customer welfare is not too large (Proposition 1). For any fixed level of sales, LIFO generates strictly greater customer welfare than FIFO issuance (Lemma 3).

Leveraging these results, Proposition 4 characterizes the retailer's optimal choice of issuance and shelf life in the case that the retailer is *required* to timestamp items and shows that this requirement strictly reduces the retailer's objective.

Proposition 4. *When the retailer is required to timestamp the items,*

a. *The optimal shelf life is strictly lower than would be optimal without timestamps: $T \leq q^{-1}(p) < T_L^*$.*

b. *The optimal policy is to use FIFO and a shelf life $T \leq q^{-1}(p)$ if and only if $f \leq \hat{f}$ for a threshold $\hat{f} \in (0, 1]$, and otherwise to use LIFO and shelf life $q^{-1}(p)$.*

c. *The optimal objective value is strictly lower than without timestamps.*

Whereas without timestamps, the retailer optimally uses LIFO and shelf life T_L^*, requiring timestamps forces the retailer to set a *strictly* lower optimal shelf life. Recall the expression of T_L^* from Theorem 1. When f is not too large, T_L^* is the maximum shelf life without timestamps $\overline{T}_L$, so $T_L^* = \overline{T}_L > q^{-1}(p)$ by (4.5). Otherwise, $T_L^* = q^{-1}(p - (p + d)/f) > q^{-1}(p)$, where the inequality is due to our assumption that the price exceeds any salvage value, $p > -d$. Thus, requiring timestamps strictly reduces the optimal shelf life, $T < T_L^*$.

With required timestamps, FIFO issuance can become optimal if the retailer puts little weight on customer welfare, $f < \hat{f}$. In this case, the shelf life constraint (4.4) motivates the retailer to shift to FIFO issuance to generate higher sales. For a retailer that maximizes direct profit ($f = 0$), the optimal shelf life with timestamps and FIFO issuance is $q^{-1}(p)$ because sales strictly increase with the shelf life for $T \in (0, q^{-1}(p)]$. For $f > 0$, the optimal shelf life with FIFO and timestamps can be strictly smaller than $q^{-1}(p)$ when that yields greater customer welfare, for example, when quality degrades rapidly.

If the retailer puts sufficient weight on customer welfare $f \geq \hat{f}$, LIFO and a shelf life $q^{-1}(p)$ are optimal. LIFO generates greater customer welfare than FIFO for any fixed level of sales, so it becomes optimal for large f. With timestamps and LIFO issuance, the maximum feasible shelf life $q^{-1}(p)$ is optimal because sales, customer welfare, and the retailer's objective all strictly increase with the shelf life for $T \in (0, q^{-1}(p)]$.

With required timestamps, the optimal shelf life in our running example is $q^{-1}(p) = 2$ for all $f \in [0, 1]$, so the left panel of Figure 2 illustrates $\hat{f}$ (dashed line) and the optimal issuance from Proposition 4.

Part (c) of Proposition 4 shows that requiring timestamps strictly reduces the retailer's objective. This occurs through two mechanisms: reduction in sales due to a shorter shelf life and reduction in purchased quality due to the shift to FIFO.

With a fixed price, Proposition 4 and Theorem 1 imply that the optimal policy for a retailer who *chooses* whether to timestamp items (jointly with the issuance and shelf life) is to *not* timestamp items and use LIFO issuance and the shelf life T_L^* defined in (4.3). In our running example, to *not* timestamp items significantly increases the retailer's objective, especially for small f or large d where T_L^* is much greater than $q^{-1}(p)$.[6]

Now suppose that the retailer *also* chooses the price $p \geq 0$ to maximize (3.4). Timestamps strictly reduce the optimal objective value and social welfare, if either $d > 0$ or $f \neq 1$. That follows from Proposition 4 and the uniqueness of the optimal policy in Proposition 2 for $f \neq 1$. If $d \leq 0$ and $f = 1$, the retailer achieves the same objective (social welfare) with timestamps as without timestamps, by setting the price equal to the salvage value, $p = -d$, and using LIFO issuance and shelf life $T = q^{-1}(-d)$.

With timestamps, the age of each item becomes observable, so the retailer conceivably could set an *age-dependent* price $p(\tau)$. Allowing for any positive $p(\tau)$ with timestamps (whereas without timestamps the price must still be uniform), the next proposition characterizes the retailer's optimal policy and objective value.

Proposition 5. *When the retailer can use age-dependent pricing with timestamps,*

a. *If $d \leq 0$, an optimal policy is to use timestamps, age-dependent price $q(\tau)$, LIFO issuance, and shelf life $q^{-1}(-d)$; the optimal objective value, issuance and shelf life are exactly the same as without timestamps.*

b. *If $d > 0$, the optimal policy is to not timestamp items and use the price, issuance, and shelf life stated in Proposition 2; timestamps would strictly reduce the objective.*

With timestamps and optimal age-dependent price $q(\tau)$, customers who find an item in stock always purchase and have zero utility, so the retailer's objective simplifies to maximizing social welfare $Q^{\pi}S^{\pi} - d(B\mu - S^{\pi})$. The retailer captures all that social welfare.

Consider the case that items have salvage value ($d \leq 0$). Social welfare is maximized with LIFO issuance and disposing of an item precisely when its value to a customer drops to the salvage value, that is, at shelf life $q^{-1}(-d)$. The retailer obtains the same optimal objective value with and without timestamps, using LIFO and shelf life $q^{-1}(-d)$. The average quality of purchased items $Q^{L,q^{-1}(-d)}$ is strictly positive, so without timestamps, the retailer optimally uses the uniform price $Q^{L,q^{-1}(-d)}$ at which customers have zero utility *on average* (whereas with newer items, customers experience strictly positive ex post utility $q(\tau) - Q^{L,q^{-1}(-d)} > 0$, and with older items, customers experience strictly negative ex post utility $q(\tau) - Q^{L,q^{-1}(-d)} < 0$). In contrast, timestamps and age-dependent price $q(\tau)$ always provide exactly zero utility; for fresher items, the optimal age-dependent price exceeds the optimal uniform price ($q(\tau) > Q^{L,q^{-1}(-d)}$), whereas for older items, that inequality is reversed.

Consider the case that items have disposal cost ($d > 0$). Because of the constraint $p \geq 0$, with timestamps, the retailer is constrained to set the shelf life $T \leq q^{-1}(0)$, whereas without timestamps, the retailer sets the *strictly larger* optimal shelf life in Proposition 2. Even with the optimal age-dependent price $q(\tau)$, timestamps strictly reduce social welfare (the retailer's objective) by forcing the retailer to reduce the shelf life.

We conclude that the retailer should *not* timestamp items. The policy characterized by Proposition 2 with no timestamps is optimal. The retailer can achieve the same optimal objective value with timestamps *only* if the item has salvage value and either $f = 1$ or the retailer can perfectly implement price $q(\tau)$ that strictly decreases with an item's age.

4.3. Insights for Regulators

Requiring grocery retailers to donate unsold food (or pay a penalty for throwing it away) increases a retailer's disposal cost d. Inducing grocery retailers to use less plastic can also increase a retailer's disposal cost d. For example, to package a rotisserie chicken with less plastic, Costco recently switched to a plastic bag, which requires more labor (costly labor, disliked by Costco's employees) to open the package to salvage a chicken (Reddit 2024).

Proposition 6 shows that regulations that increase a retailer's disposal cost d may have pernicious effects: reduced quality and quantity of donations and reduced customer welfare. The proposition addresses the case with an exogenously fixed price and the case with an optimal price set at p_L^* to maximize Objective (3.4).

Proposition 6. *Increasing the disposal cost d*

a. *Decreases the amount and quality of disposed items (strictly if $d < \hat{d}$);*

b. *Decreases customer welfare (strictly if $d < \hat{d}$ and p is fixed), where $\hat{d} := f(p - q(\overline{T}_L)) - p$ for the case with exogenously fixed price and $f > 0$, $\hat{d} := -\infty$ for the case with exogenously fixed price and $f = 0$, and $\hat{d} := -q(\overline{T}_L(0))$ for the case that the retailer chooses the price.*

The rationale for (a) is that increasing the disposal cost d increases the optimal shelf life, which reduces disposals and the quality of disposed items. Those results are strict for $d < \hat{d}$ because that is where the shelf life constraint $T \leq \overline{T}_L$ is nonbinding.

The rationale for (b) is that if p is fixed and $d < \hat{d}$, the optimal shelf life is $q^{-1}(p - (p + d)/f)$, at which an item's quality is strictly less than the price. Increasing d and thereby increasing this optimal shelf life generates sales of items with $q(\tau) < p$, which strictly decreases customer welfare. Customer welfare is invariably zero if $d \geq \hat{d}$ and at price p_L^*.

Ironically, the strict decrease in customer welfare, disposals, and disposed items' quality with d occurs only when $f > 0$ and the retailer provides strictly positive customer welfare.[7] For moderate and large f, in the running example, customer welfare, disposals, and disposed items' quality *significantly* decrease with d; details are in Section EC.4 of the Online Appendix.

5. Results of Model Extensions

Whereas in our base model, LIFO issuance and to *not* timestamp are optimal, this section identifies alternative modeling assumptions that can change *one* of those results. FIFO issuance can become strictly optimal due to an upper bound on the shelf life, age-dependent disposal cost, holding cost, or customer risk or loss aversion. Timestamps can become strictly optimal due to heterogeneity in customers' utility from the premade food. For each of these model extensions, in Sections 5.1–5.5, we study the jointly optimal choice of issuance and whether to timestamp items, with exogenously fixed price p.

5.1. Upper Bound on Shelf Life

Under the U.S. Food and Drug Administration's Food Code, to hold a hot premade food like rotisserie chicken, a retailer must either maintain the temperature of the food above 135°F (57°C) to prevent bacterial growth or limit the shelf life to a maximum of four hours (USDA 2022). In other words, a retailer that does not maintain the temperature above 135°F has an exogenous upper bound of four hours on the shelf life.

Proposition 7 shows how an exogenous upper bound on the shelf life changes the optimal issuance and whether to timestamp items. (Remember, for comparison, that in the base model, LIFO is uniquely optimal and timestamps strictly reduce the objective.)

Proposition 7. *With an exogenous upper bound on the shelf life* $T \leq \overline{T}$,

a. *FIFO issuance strictly dominates LIFO issuance if and only if* $f < f^{\text{UB}} \in [0,1]$.

b. *To not timestamp is optimal. Timestamps strictly reduce the objective if and only if* $\overline{T} > q^{-1}(p)$ *and* $f \in [0, \hat{f}^{\text{UB}}) \cup (f^{\text{UB}}, 1]$ *for* $\hat{f}^{\text{UB}} \in [0, f^{\text{UB}}]$.

The rationale for (a) is that for any target level of sales, LIFO generates greater customer welfare than FIFO, but LIFO requires larger shelf life to achieve that level of sales. The threshold satisfies $f^{\text{UB}} > 0$ when the upper bound $\overline{T}$ is strictly lower than the shelf life T where sales with LIFO equal the maximum sales with FIFO, $S^{L,T} = S^{F,\overline{T}_F}$. In that case, to maximize sales requires FIFO issuance, so FIFO is strictly optimal for a retailer that sufficiently prioritizes sales over customer welfare, that is, has $f < f^{\text{UB}}$.

The rationale for (b) is that timestamps constrain the shelf life to $T \leq q^{-1}(p)$, so can never be strictly optimal. If $\overline{T} > q^{-1}(p)$, timestamps strictly reduce the objective in the case that LIFO is optimal without timestamps ($f > f^{\text{UB}}$) because the optimal shelf life with LIFO strictly exceeds $q^{-1}(p)$. Timestamps also strictly reduce the objective if the retailer is sufficiently focused on sales ($f < \hat{f}^{\text{UB}}$) to the extent that, without timestamps, the retailer optimally uses FIFO and a shelf life $T > q^{-1}(p)$. Only at intermediate f might the retailer be indifferent to timestamps; this occurs when the retailer (with or without timestamps) would optimally use FIFO and set a low shelf life $T \leq q^{-1}(p)$ to boost customer welfare.

5.2. Age-Dependent Disposal Cost

Suppose that the disposal cost increases with the age of the disposed item, that is, increases with the shelf life T. Specifically, the disposal cost d becomes $d(T) = \delta \cdot T$, where $\delta > 0$.

Proposition 8. *With age-dependent disposal cost,*

a. *FIFO issuance can strictly dominate LIFO issuance.*

b. *To not timestamp is optimal. Timestamps can strictly reduce the objective.*

In our running illustrative example, Figure 3 shows that FIFO is strictly optimal when f is small and the rate of increase in disposal cost δ is large. Large δ incentivizes a reduction in the shelf life, which acts like the upper bound on shelf life in Section 5.1 to favor FIFO for small f. Timestamps strictly reduce the objective in the parameter regions labeled "NO T.S." Timestamps have no effect in the region labeled "T.S *or* NO T.S.," where FIFO is optimal and large δ and large f push the optimal shelf life below $q^{-1}(p)$.

5.3. Variable Holding Cost

Suppose that the retailer incurs holding cost $h > 0$ per item per unit time on the shelf.

Proposition 9. *With nonzero variable holding costs,*

a. *FIFO issuance can strictly dominate LIFO issuance.*

b. *To not timestamp is optimal. Timestamps can strictly reduce the objective.*

In our running example, for small f, the optimal issuance is *nonmonotonic* in the holding cost h. LIFO is strictly optimal for $h = 0$. As shown in Figure 4, for small f, FIFO is strictly optimal at $h = 0.2$, whereas LIFO is strictly optimal at the larger holding cost $h = 1$.

Our finding that incorporating a holding cost can favor FIFO arises from the joint optimization of shelf

Figure 3. Effect of Age-Dependent Disposal Cost $d(T) = \delta \cdot T$ on Optimal Issuance and Timestamp Policy

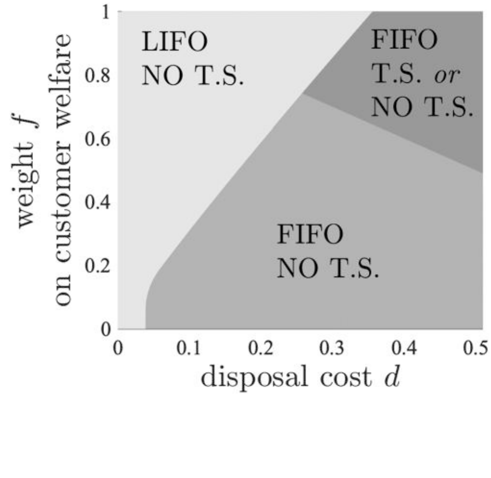
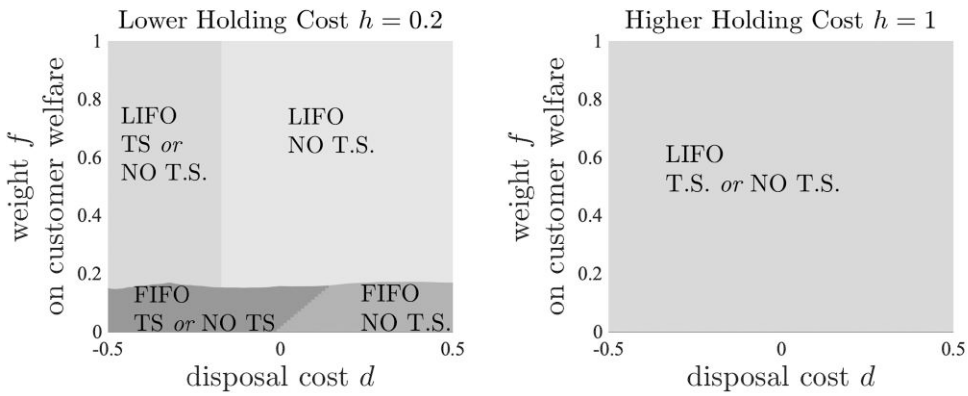


Figure 4. Effect of Holding Cost on Optimal Issuance and Timestamp Policy



life and issuance. In contrast, prior literature (Parlar et al. 2011, Chen et al. 2014) assumed *fixed* shelf life and found that holding cost favors LIFO.

Timestamps strictly reduce the objective when the holding cost h is small enough and disposal cost d is large enough that the optimal shelf life strictly exceeds $q^{-1}(p)$, the parameter regions labeled "No T.S." in the left panel of Figure 4.

5.4. Strict Concavity in Quality Degradation, Risk Aversion, or Loss Aversion

Suppose that customer utility is strictly concave in the age of an item. Specifically, a customer's utility from purchasing an item of age τ at price p is $u(\tau) - p$, where $u(\tau)$ is strictly concave and decreasing with τ. The strict concavity could represent customer risk aversion. The strict concavity could also arise from the quality degradation schedule. (We had previously assumed that a customer's utility from purchasing an item of age τ at price p is $q(\tau) - p$ with weak convexity in the quality degradation schedule $q(\tau)$.)

Let us also consider loss aversion, in which a customer's utility from purchasing an item of age τ at price p is $q(\tau) - p - \ell[p - q(\tau)]^+$ where $\ell \geq 0$.

Proposition 10. *With strictly concave utility or loss aversion,*

a. *FIFO issuance can strictly dominate LIFO issuance.*

b. *To not timestamp is optimal. Timestamps strictly decrease the objective if* $f \leq \hat{f}^{\ell}$*, for some threshold* $\hat{f}^{\ell} \in (0, 1]$.

Incorporating loss aversion into the running example, Figure 5 shows that FIFO becomes strictly optimal when f is small, d is large, or loss aversion ℓ is large, and that timestamps strictly reduce the objective. An analogous figure with strictly concave utility in Section EC.6 of the Online Appendix shows that small f, large d, and greater risk aversion favor FIFO issuance.

In comparison with LIFO, FIFO reduces variation in the age of the item, so with concave utility FIFO increases customers' average utility from a purchased item (as in Jensen's inequality). FIFO also results in fewer sales of the oldest items, just before disposal, which increases customers' average utility when customers exhibit high loss-aversion (large ℓ). The increase in average utility increases customer welfare and also enables a retailer who does not use timestamps to increase sales by using a larger shelf life.

5.5. Heterogeneous Customers

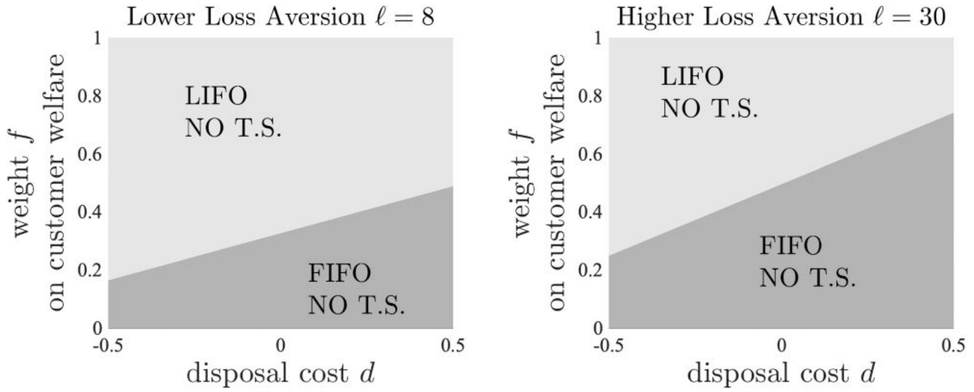
Suppose that the utility from purchasing an item of quality $q(\tau)$ at price p is $u(\theta, q(\tau)) - p$, which increases with a customer's type θ and increases linearly with quality $q(\tau)$.[8] The distribution of θ has bounded support in the interval $[\theta_\ell, \theta_h]$ and $u(\theta_\ell, q(0)) > p$.[9] With timestamps, a customer of type θ purchases an item of age τ and corresponding quality $q(\tau)$ if and only if $u(\theta, q(\tau)) \geq p$. Without timestamps, he purchases an item if and only if $u(\theta, Q) \geq p$, where Q denotes the (long-run average) quality of purchased items.

Our main result regarding issuance, established in Section 4.1, holds.

Theorem 2. *Without timestamps, the retailer optimally uses LIFO issuance.*

LIFO outperforms FIFO for essentially the same reason as in the base model with homogeneous customers: LIFO enables the retailer to increase the shelf life and generate greater sales and customer welfare. In a rational equilibrium without timestamps, customers with θ above a threshold all purchase an item, if an item is in stock. At the resulting average purchased quality and θ threshold, utility equals the price. A challenge in proving Theorem 2 is that with a given issuance and shelf life, multiple rational equilibria may exist. We prove that in such cases, a Pareto dominant equilibrium exists, which is the equilibrium with highest sales, highest purchased quality, and highest customer welfare. Intuitively, when a larger fraction of arriving customers will

Figure 5. Effect of Loss Aversion on Optimal Issuance and Timestamp Policy



purchase an item if they find one in stock, items wait for less time on the shelf, so are purchased at a higher quality level. Like in the base model, we assume that the retailer can induce the Pareto dominant (higher sales) equilibrium. Section EC.8 in the Online Appendix explains practical ways in which this can be achieved.

With heterogeneous customers, timestamps can become strictly optimal. One mechanism is that *timestamps can strictly increase sales*. To study this, let us focus on the following class of problems. Here, $g : (-\infty, 1] \longrightarrow \bar{\mathbb{R}}^+$ is an extended-real function defined as the inverse of the function $x/(e^x - 1)$ for $x > 0$ and as $g(x) = +\infty$ for $x \leq 0$.

Problem Class 5.1. *A customer's utility from purchasing an item of quality $q(\tau)$ at price p is $\theta + q(\tau) - p$. The type θ takes value θ_ℓ with probability $1 - \beta$ and θ_h with probability β, where $\theta_h \geq \theta_\ell$. The quality degradation schedule is linear: $q(\tau) = q_0 - b\tau$. The replenishment process has batch size $B = 1$ and interarrival time $\ell_n \geq \frac{1}{\beta\lambda} g(1 - \beta\lambda(q_0 + \theta_h - p)/b)$ almost surely.*

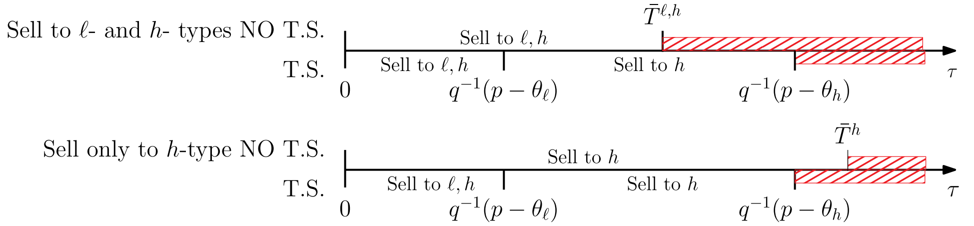
In this problem class, with the optimal shelf life, at most one item is on the shelf, so we can study the direct effect of timestamps on sales, disentangled from the choice of issuance.

Without timestamps, two cases arise. In Case 1, the optimal shelf life $\overline{T}^{\ell,h}$ is short enough that *both* types of customers will purchase an item. In Case 2, the optimal shelf life $\overline{T}^{h}$ is so long that only h-types will purchase an item. We refer to customers of type θ_h and θ_ℓ as h-type and ℓ-type, respectively, mnemonic for $h$igh and ℓow willingness to pay.

In Case 1 and Case 2, as depicted in Figure 6, timestamps increase sales to one type of customer but reduce sales to the other type. With timestamps, the optimal shelf life is the largest age at which an h-type will purchase an item, $q^{-1}(p - \theta_h)$, and although an item's age is sufficiently low, $\tau \leq q^{-1}(p - \theta_\ell)$, an arriving customer of either ℓ- or h-type will purchase the item. In Case 1, timestamps increase sales to h-types by increasing the shelf life: $q^{-1}(p - \theta_h) > \overline{T}^{\ell,h}$, but reduce sales to ℓ-types by reducing the maximum age at which an ℓ-type will purchase an item, from $\overline{T}^{\ell,h}$ to $q^{-1}(p - \theta_\ell) < \overline{T}^{\ell,h}$. In Case 2, timestamps enable the retailer to sell to ℓ-types, but reduce sales to h-types by reducing the maximum age at which an h-type will purchase an item, from $\overline{T}^{h}$ to $q^{-1}(p - \theta_h) < \overline{T}^{h}$.

Proposition 11 grounds this discussion by providing an expression for the shelf life that maximizes sales in each case and characterizes the precise conditions under which timestamps strictly increase sales (are strictly optimal at $f = 0$).

Figure 6. (Color online) Effect of Timestamps on Optimal Shelf Life and Sales, Depending on Whether (with No Timestamps) the Retailer Sells to Both Types vs. Only h-Types



Note. Dashed area indicates that no sales could occur.

Proposition 11. *For a retailer that aims to maximize sales in Problem Class* 5.1,

a. *The optimal shelf life without timestamps is*

$$\overline{T}^{\ell,h} = \frac{1}{\lambda} g(1 - \lambda q^{-1}(p - \theta_\ell)),$$

if selling to both customer types and

$$\overline{T}^{h} = \frac{1}{\beta\lambda} g(1 - \beta\lambda q^{-1}(p - \theta_h)),$$

if selling only to the h-types, the optimal shelf life with timestamps is $q^{-1}(p-\theta_h) = (q_0 + \theta_h - p)/b$, *and these satisfy* $q^{-1}(p-\theta_\ell) = (q_0 + \theta_\ell - p)/b < \overline{T}^{\ell,h} < q^{-1}(p-\theta_h) < \overline{T}^{h}$.

b. *Timestamps strictly increase sales if and only if*

$$0 < \Delta_1 := e^{-\lambda\overline{T}^{\ell,h}} - \beta e^{-\lambda q^{-1}(p-\theta_h)} - (1-\beta)e^{-\lambda q^{-1}(p-\theta_\ell)},$$

$$0 < \Delta_2 := 1 - \beta + \beta e^{-\lambda\overline{T}^{h}} - \beta e^{-\lambda q^{-1}(p-\theta_h)} - (1-\beta)e^{-\lambda q^{-1}(p-\theta_\ell)},$$

in which case, the increase in sales from using timestamps is $\min(\Delta_1, \Delta_2)$.

c. *The following are sufficient conditions for* $\min(\Delta_1, \Delta_2) > 0$:

$$\beta \in (0,1), \tag{5.1a}$$

$$\theta_\ell < p - q_0 + \frac{b}{\lambda}\frac{\beta + (1-\beta)\ln(1-\beta)}{\beta}, \tag{5.1b}$$

$$\theta_h > -\frac{1}{\lambda}\ln\frac{(1-\beta)(1-e^{-\frac{\lambda(q_0+\theta_\ell-p)}{b}})}{\beta}. \tag{5.1c}$$

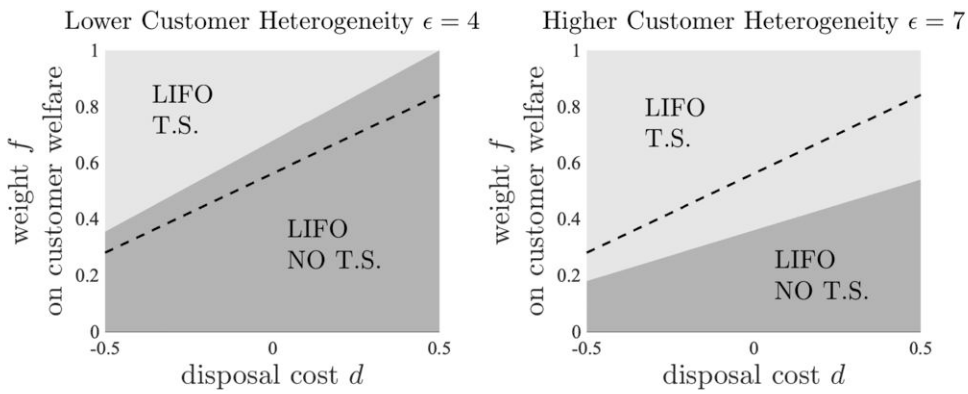
Part (b) provides necessary and sufficient conditions for timestamps to strictly increase sales. The expressions for Δ_1 and Δ_2 represent the difference in sales between the optimal policy with timestamps and the optimal policy without timestamps in Case 1 (selling to ℓ- and h-types) and Case 2 (selling only to h-types), respectively. That $\Delta_1 > 0$ and $\Delta_2 > 0$ means that the sales with timestamps exceed the retailer's maximum sales without timestamps. These two conditions imply that $\beta \in (0,1)$: Customers must be heterogeneous for timestamps to strictly increase sales.

Part (c) provides sufficient conditions for timestamps to strictly increase sales. These highlight the importance of customer heterogeneity by showing that timestamps strictly increase sales if $\beta \in (0,1)$, θ_ℓ is sufficiently low, and θ_h is sufficiently high. The upper bound on θ_ℓ in (5.1b) and the lower bound on θ_h in (5.1c) strictly increase with the rate of quality degradation b and strictly decrease with the customer arrival rate λ. The sufficient conditions in (c) are derived by requiring that without timestamps the retailer prefers selling only to h-types and requiring that sales with timestamps exceed an artificial upper bound on the sales to h-types without timestamps (calculated by assuming a h-type buys any item in stock and the retailer never disposes of an item). The bounds in (5.1b) and (5.1c) partly originate from requiring that without timestamps the retailer prefers to sell only to h-types; lower θ_ℓ and higher θ_h favor that regime by lowering the incentive to sell to ℓ-types (who would require reduction in the shelf life to be convinced to purchase). Moreover, higher θ_h increases the shelf life and sales with timestamps, without changing the artificial upper bound on sales to h-types without timestamps.

In our general model, if timestamps increase sales (are optimal at $f = 0$), then timestamps are strictly optimal for $f \in (0,1]$. In general, timestamps are strictly optimal if and only if $f > \underline{f}$ for some threshold $\underline{f}$. The reason is that *timestamps increase customer welfare* by preventing a customer from making a purchase with negative utility $u(\theta, q(\tau)) - p < 0$ and, with heterogeneous customers, by improving the allocation of items to customers with higher θ and correspondingly higher utility from obtaining an item. When a customer with small θ decides (based on the timestamp) not to purchase an item, a subsequently arriving customer with higher θ is enabled to purchase it. Incorporating customer heterogeneity in the running example, Figure 7 shows that $\underline{f} > 0$: Timestamps decrease sales and become optimal only through the second mechanism of increased customer welfare. The threshold $\underline{f}$ above which timestamps are optimal decreases with the extent of customer heterogeneity and increases with the disposal cost d.

LIFO issuance is optimal in all our numerical experiments (detailed in Section EC.7 of the Online Appendix). Theorem 2 established that LIFO is optimal without timestamps, so the key numerical finding is that *LIFO is optimal whenever timestamps are strictly optimal*. This is surprising in light of Proposition 4b (the optimality of FIFO for $f \le \hat{f}$ with homogeneous customers and required timestamps), yet has two rationales. First, with low customer heterogeneity, timestamps are strictly optimal only for large f: where LIFO would be optimal if customers were homogeneous and timestamps required. This is illustrated in the left panel of Figure 7, where the dotted line is the threshold $\hat{f}$ of Proposition 4b. The second rationale is that, with timestamps, larger customer heterogeneity favors LIFO issuance so that LIFO becomes optimal even for $f \in [\underline{f}, \hat{f})$, as in the right panel of Figure 7. LIFO issuance increases the optimal shelf life, which increases sales and increases customer welfare, especially by improving allocation among highly heterogeneous customers. These two rationales are numerical observations. To prove that LIFO is always optimal with heterogeneous customers and a uniform price, the foundational

Figure 7. Optimal Issuance and Timestamp Policy with $u(\theta, q(\tau)) = \theta + q(\tau)$ and θ Uniformly Distributed in $[0, \epsilon]$



Note. Dashed line is $\hat{f}$, below which FIFO would be optimal if customers were homogeneous and timestamps required.

challenge is in performance characterization for non-LIFO issuance with timestamps and heterogeneous customers.

By enabling age-dependent pricing (price discrimination among heterogeneous customers) timestamps could become optimal in a larger parameter region. Atan et al. (2023) show benefits of two-level age-dependent pricing and complex non-LIFO issuance in a complementary model.

6. Conclusions

This paper introduces a model of a grocery retailer's management of premade food, with several key features. Each item's quality strictly decreases with its time on the shelf (age) in a weakly convex manner, so that the quality experienced by customers varies depending on the stochastic process by which customers arrive relative to the stochastic process by which food is made in the store. Without timestamps, a customer decides whether to purchase an item based on the average quality of purchased items. In contrast, with timestamps, a customer observes the quality of the item on offer, and decides accordingly. To the best of our knowledge, this paper is the first to consider the optimal *joint* choice of shelf life and issuance order, and the first to analyze a retailer's decision of whether to timestamp items.

In a base model, the paper shows that a retailer should issue items to customers LIFO rather than FIFO. FIFO issuance is widely assumed in the academic literature on perishable inventory management and FIFO issuance is also used by many grocery retailers, for the same reason: FIFO is thought to maximize sales and minimize waste. To the contrary, we prove that using LIFO rather than FIFO maximizes sales and minimizes waste. The rationale is that switching to LIFO increases the quality of purchased items, which enables the retailer to increase the shelf life, and thereby increase sales and reduce waste. For any target level of sales, LIFO generates higher customer welfare than does FIFO.

However, incorporating a holding cost, upper bound on the shelf life, requirement to timestamp items, or age-dependent disposal cost can favor FIFO issuance. To achieve a target level of sales, LIFO requires a longer shelf life than FIFO. Hence, when a retailer prioritizes sales over customer welfare and is forced to shorten the shelf life, FIFO can dominate LIFO. Indeed, the result that holding cost can favor FIFO arises from the *joint* choice of issuance and shelf life. This is the opposite of the result in (Parlar et al. 2011, Chen et al. 2014) that, assuming *fixed* shelf life, a holding cost favors LIFO issuance.

Incorporating customer loss aversion or risk aversion also can favor FIFO over LIFO issuance, if the disposal cost is low and the retailer prioritizes sales over customer welfare.

With homogeneous customers, in the base model and with all the aforementioned model extensions, to *not* timestamp the premade food is optimal. Timestamps effectively reduce the shelf life and thereby reduce sales and increase waste.

When customers are heterogeneous in their willingness to pay for the premade food, timestamps can become strictly optimal. Timestamps can increases sales, in cases with highly heterogeneous customers, and always increase customer welfare.

Lastly, the paper shows that requiring a retailer to donate unsold food motivates the retailer to increase the shelf life, which reduces the quantity and the quality of donated food, and also reduces the average quality of food sold to customers. That helps to explain the problem that donated food commonly goes to waste because of its low quality.

A direction for future *empirical* research, as states and municipalities require retailers to donate unsold food or impose other regulations to divert food from landfills, is to measure changes in retail operations, food quality, sales, and waste. Another is to quantify how issuance, shelf life, pricing, or timestamps affect food sales, waste and quality, and customer welfare, for example, as Costco is now starting to timestamp rotisserie chickens. Directions for *analytical* research are to consider a limited shelf space for the display of multiple types of premade food, age-dependent pricing, and the foundational challenge in performance characterization of non-LIFO issuance with timestamps and heterogeneous customers.

Endnotes

[1] Food production accounts for roughly a quarter of anthropogenic greenhouse gas emissions (Vermeulen et al. 2012). A third of unsold food in the United States goes to landfill and produces methane, a potent greenhouse gas (ReFED 2021).

[2] More than 700 million people go hungry and 2 billion are food insecure, including 44 million in the United States.

[3] See https://www.reddit.com/r/EatCheapAndHealthy/comments/dqpa0t/rotisserie_chicken/, accessed January 4, 2023.

[4] See https://www.amazon.com/product-reviews/B07FZJ4245, accessed January 4, 2023.

[5] For $f = 0$, the shift from FIFO to LIFO increases the shelf life by 275%, increases sales by 7%, reduces disposals by 27% and thus increases the retailer's objective by an amount that increases with d, from 3% at $d = -0.5$ to 12% at $d = 0.5$; customer welfare remains at 0. For $f = 1$, the shift from FIFO to LIFO increases the shelf life by 82% to 116%, increases customer welfare by 13% to 18%, and increases the retailer's objective by 6% to 16% as d ranges from -0.5 to 0.5. Details and illustrations are in Section EC.4 of the Online Appendix.

[6] The amount of increase in the objective varies monotonically with f and d. For $f = 0$ it ranges from 15% to 86% and for $f = 1$ it ranges from 1% to 15%, as d ranges from -0.5 to 0.5. Details and illustrations are in Section EC.4 of the Online Appendix.

[7] Recall from Proposition 2 that any price in $[\max(0, -d), p_L^*]$ maximizes the objective at $f = 1$, and the choice of price in that range determines the distribution of the total welfare between customers and the retailer. If instead of the p_L^* that maximizes the retailer's direct profit, the retailer were to choose a constant price in $[\max(0, -d), p_L^*)$ or a price that decreases with d, the customer welfare would strictly decrease with d.

[8] In the most general form, $u(\theta, q(\tau)) = u_1(\theta) + u_2(\theta) \cdot q(\tau)$ where $u_1(\theta)$ and $u_2(\theta)$ are increasing functions of θ.

[9] This replaces our base model assumption $q(0) > p$; the retailer would have zero sales to customers with $u(\theta, q(0)) \le p$.

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