Economic and environmental analysis of processing plant interventions to reduce fluid milk waste

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ABSTRACT

With the increased awareness about the economic and environmental impact of food waste, many interventions along food supply chains have been proposed to mitigate food waste. Even though interventions used to target food waste usually revolve around logistics and operations management, we highlight a unique solution to address this issue, specifically for fluid milk. We target the intrinsic quality of fluid milk by evaluating interventions that will extend the product shelf life. We used data from a previous fluid milk spoilage simulation model, collected price and product information from retail stores, conducted an expert elicitation, and used hedonic price regressions to determine the private and social gains to the dairy processing plant when implementing 5 different interventions to extend shelf life. Our data suggest that the value of each additional day of shelf life is approximately $0.03 and indicate that increasing periodic equipment cleaning is the most cost-effective strategy for processing plants to achieve fluid milk shelf-life improvements, both from a firm’s economic standpoint and from an environmental standpoint. Importantly, the approaches reported here will be valuable to help individual firms to generate customized facility and firm specific assessments that identify the most appropriate strategies for extending the shelf life of different dairy products.

Key words: shelf life, dairy processing plant, economic impact, environmental impact, food waste

INTRODUCTION

Globally and nationally, food waste is increasingly being recognized as a significant issue. Even though the terms food loss and food waste are used interchangeably, food loss refers to the decrease in the quantity or quality of food resulting from decisions and actions by food suppliers in the chain, excluding retailers, food service providers, and consumers, whereas food waste is a result of decisions and actions by retailers, food service providers, and consumers (FAO, 2019). In the context of dairy, for example, product discarded during cleaning or line changes at a milk processor is food loss, whereas product discarded when consumers dispose of milk after its code date is food waste. According to the Food and Agriculture Organization of the United Nations (FAO), one-third of the food produced is wasted globally (Gustavsson et al., 2011; FAO, 2019). Food waste has also been estimated to generate 4.4 GtCO₂e or 8% of greenhouse gases globally (FAO, 2011). Specifically, in the United States, dairy products have been estimated in the past to be among the top 3 food groups representing the largest share of the total volume of food wasted, with fluid milk estimated to be responsible for approximately 65% of dairy food waste by weight (Buzby et al., 2014). In the same study, the value of fluid milk waste in the United States was estimated to be $6.4 billion per year (Buzby et al., 2014). Alongside the financial concerns associated with fluid milk waste, there are environmental implications associated with fluid milk waste. These environmental implications can be determined using carbon dioxide equivalent (CO₂e), which measures how much a greenhouse gas contributes to global warming, relative to carbon dioxide (Brander, 2012). Globally, fluid milk production, processing, and transport has been estimated to be responsible for 2.4 kg of CO₂e per kg of milk and to represent 2.7% of global anthropogenic greenhouse gas emissions (FAO, 2010; Gerber et al., 2013). The economic and environmental consequences of fluid milk waste underline the need for targeted initiatives that can address this issue. Many possible approaches to help tackle the food waste challenge have been reported in both the operations and retail management literature. In the operations management literature, interventions typically focus on case size, supply chain aging, manufacturer’s sales incentives, replenishment workload, and minimum
order rule to reduce product expiration (Akkas et al., 2019). In retail management, interventions typically focus on markdown management and shelf availability and allocation (Hu et al., 2016; Teller et al., 2018). Research has largely addressed food waste as a logistical problem and suggested solutions target operations and retail management. This literature, however, inadequately evaluates solutions for food waste that can improve the products intrinsically (e.g., by extending shelf life).

There are many technologies and solutions that can be used to improve the intrinsic quality and extend the shelf life of fluid milk, thereby also serving to mitigate food waste (e.g., by reducing the amount of product that is discarded as it exceeded the best-by date). On-farm intervention strategies can be implemented to reduce transmission of bacterial spores in raw milk that can ultimately improve the quality of the milk and reduce fluid milk waste due to microbial spoilage (Murphy et al., 2016; Martin et al., 2021). Another solution to improving the intrinsic quality of the food is through applying interventions at the processing plant. To address this, Buehler et al. (2018) and Lau et al. (2022a) developed Monte Carlo models that assessed interventions processors can apply at the dairy plant to reduce fluid milk spoilage. Fluid milk is an example of a perishable good that is in a unique position whereby improvements can be made intrinsically, without the use of technologies that may have reduced consumer acceptability (e.g., use of nonclean label additives that reduce microbial or chemical spoilage) and where shelf life date can be extended by applying interventions at the processing plant.

In this paper, we evaluate the potential economic and environmental implications of several possible interventions that can be made at a dairy processing plant to reduce fluid milk waste. We leverage a previously published Monte Carlo simulation model that predicts spoilage of pasteurized fluid milk due to pasteurization contamination (Lau et al., 2022a) to estimate the effects of different intervention strategies. We address existing gaps in cost data by using expert elicitation, a systematic process whereby expert judgment is collected and formalized (US EPA, 2011; Hoelzer et al., 2012) to generate reliable cost estimates associated with different intervention strategies. Then, we conducted an expert elicitation (Wiedlea, 2008; Hoelzer et al., 2012) to estimate the cost of implementing each intervention strategy. We also collected price and product data of half-gallons of fluid milk both in-store and online. Lastly, we collected data on the environmental impact of fluid milk and parametrized it to estimate the amount of CO₂ emissions associated with fluid milk spoilage and to determine the social cost of CO₂ emissions associated with fluid milk spoilage. In the following sections, we describe in detail each of these sources of data.

Shelf-Life Estimation Using a Postpasteurization Contamination Monte Carlo Simulation

A previously described Monte Carlo simulation model was used to predict the shelf life of half-gallon (1.89 L) fluid milk containers when implementing 5 different interventions at dairy processing plants to address postpasteurization contamination: (i) seek and destroy, (ii) improved preventative maintenance (PM) procedures, (iii) increased periodic equipment cleaning (PEC), (iv) addition of temperature sensors to half-gallon packaging, and (v) application of antimicrobial coating to floor drains (Lau et al., 2022a).

The first intervention, (i) seek and destroy, represents a strategy where one specific strain of spoilage bacteria that is habitually found in a specific place or niche in a facility is responsible for a substantial proportion of fluid milk spoilage issues. Addressing this issue involves finding and removing the niche and would not be an ongoing intervention; we assume that once this niche has been removed, the facility will no longer have a problem with fluid milk spoilage due to this bacterial strain.

Implementing the second intervention, (ii) improved PM procedures, can include improved standard operating procedures to replace equipment parts before they wear out and contribute to bacterial contamination of finished products; this is an ongoing intervention that reduces overall occurrence of finished product contamination with spoilage organisms.

In addition to Clean-In-Place sanitation regimens, PEC, which is labor intensive and involves equipment
disassembly, is essential to control postpasteurization contamination. Due to the manual, labor-intensive nature of PEC, plants will use different PEC frequencies. As increased PEC frequency is predicted to reduce postpasteurization contamination with spoilage organisms, we evaluated (iii) increasing PEC frequency as the third intervention.

The fourth intervention we evaluated, (iv) the addition of temperature sensors to half-gallon packaging, can also be an effective way to extend the shelf life of fluid milk. This intervention would be implemented by placing a temperature sensor on each milk carton. The sensor would indicate when fluid milk exceeds a target temperature range (or a given time-temperature combination threshold) and could also be used with predictive models to allow for package specific shelf-life information (i.e., smart label; Lau et al., 2022b). These approaches can reduce unnecessary discarding of product that is not spoiled.

Because contamination can occur through aerosolized bacteria, the fifth intervention, (v) evaluated use of antimicrobial coating on floor drains, which is expected to reduce fluid milk contamination (e.g., at the packaging stage). This contamination is a result of aerosolization of bacteria found in processing plant environments (e.g., due to cleaning with high-pressure hoses) and an antimicrobial coating on the floor drains is expected to reduce bacterial numbers on floors and hence reduce the number of aerosolized bacteria. This intervention was included as an example of interventions that use infrastructure and facility improvements to extend fluid milk shelf life.

To simulate implementation of each of the 5 interventions in the model, the model parameters for postpasteurization contamination frequency as well as the inputs for initial spoilage organism concentration in fluid milk and the storage temperature were changed to reflect the expected effect of different interventions (see Table 1 for details). For example, the temperature distribution was truncated at 6°C to represent the use of a temperature sensor to remove fluid milk containers that exceed 6°C (Table 1).

The MC model predicts the concentration of psychrotolerant gram-negative bacteria introduced as postpasteurization contamination in half-gallon fluid milk containers across 14 d of shelf life. We used this model to generate 100,000 observations for each specific implementation of a given intervention; for some interventions 2 different levels of implementing were modeled with 100,000 observations per level of implementa-

<table>
<thead>
<tr>
<th>Intervention</th>
<th>Implementation in a processing plant</th>
<th>Inputs changed in the base PPC model used to evaluate the intervention effects</th>
<th>Implementation in the PPC model</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) Seek and destroy</td>
<td>The processing plant has one main bacterial strain that causes PPC. This strain has a specific niche. This intervention involves finding and removing/remediating this niche. Assumes that this is a facility by and large has microbial contamination under control; this is an annual intervention.</td>
<td>Frequency</td>
<td>(i) Set frequency of contamination for specific strain (“ST”) to 0</td>
</tr>
<tr>
<td>(ii) Improved preventative maintenance (PM) procedures (e.g., improving standard operating procedures (SOPs) and checklists to ensure appropriate PM scope and frequency)</td>
<td>This processing plant only replaces equipment parts when they see obvious wear and tear or when equipment fails; they will change from this to a standard, industry best practices PM program. However, this is only one source of PPC. There are still other sources of contamination that are not addressed with this intervention.</td>
<td>Initial concentration</td>
<td>(i) Reduced by 1 log_{10} (ii) Reduced by 3 log_{10}</td>
</tr>
<tr>
<td>(iii) Increase periodic equipment cleaning (PEC) (i.e., taking it apart, cleaning, reassembling) on filler nozzles from once a week to twice a week; includes replacement of old filler nozzles.</td>
<td>A processing plant only takes apart equipment once a week and will increase it to twice a week to clean and then reassemble. The plant will also replace old filler nozzles that carry an increased risk of microbial contamination (e.g., through biofilm formation).</td>
<td>Frequency</td>
<td>(i) Reduced from 100% to 50% (ii) Reduced from 100% to 10%</td>
</tr>
<tr>
<td>(iv) Addition of temperature sensor to half-gallon packaging</td>
<td>A temperature sensor will be placed on each milk carton. This will indicate if the product ever goes beyond 6°C. If it exceeds the temperature range, that product will be disposed of.</td>
<td>Temperature</td>
<td>Truncate temperature distribution at 6°C</td>
</tr>
<tr>
<td>(v) Application of antimicrobial coating to floor drains</td>
<td>An antimicrobial coating will be used on the floor drains of the processing plant to reduce the cell density of aerosolized bacteria.</td>
<td>Initial concentration</td>
<td>Initial concentration reduced by 2 log_{10} for 10% of samples</td>
</tr>
</tbody>
</table>

Table 1. Previously developed postpasteurization contamination (PPC) model summary
mentation (Table 1). For example, for intervention (ii), improved PM procedure, the 2 levels of implementation were assumed to reduce initial concentration of psychrotolerant gram-negative bacteria by either 1 log10 or 3 log10. In contrast, for intervention (iv), addition of temperature sensors, we modeled only one level of implementation (i.e., truncate temperature distribution at 6°C).

Of note, our study focused on the type of shelf life and shelf-life labeling that is typical for HTST-pasteurized fluid milk in the United States, which is a single shelf-life date (typically expressed as sell-by or best-by). Even though other products or countries may use labeling approaches that include both a sell-by or best-by date as well as a “consume within X days of opening” recommendation, these types of dual dates are typically not applicable to HTST-pasteurized milk. In addition, the interventions assessed here would be expected to predominantly affect the sell-by or best-by date.

**Intervention Cost Data**

The costs associated with each intervention are based on a hypothetical 6,000 square feet (557 m²) fluid milk–processing plant with 6 to 7 production lines and 25 drains in total. This hypothetical processing plant produces 300,000 pounds (136,078 kg) of milk per day, which is approximately 68,900 half-gallons (130,407 L) per day. Expert elicitation (Rowe and Wright, 1999; Colson and Cooke, 2018) was conducted to approximate the costs for interventions (i)–(iii). The participants of the expert elicitation are involved in a variety of extension activities for dairy farmers and processors and have extensive experience in the quality and safety of milk and dairy products. Some of the key costs considered for these interventions include consultant costs, downtime, and labor costs (more details in Table 2). For intervention (iv), the addition of temperature sensors to half-gallon packaging, the key cost considered was the cost of each individual sensor for each half-gallon. For intervention (v), the application of antimicrobial coating to the floor drains intervention, the key costs considered were the cost of the coating for the floors, the downtime required, and the time required between reapplication of a new coating (Table 2). The total amortized cost for the floor was calculated based on a $48,000 loan over 10 yr with an interest rate of 5%. Based on the data collected, the (i) seek and destroy intervention would require the most labor. Even though it appears that most of the work will be done by the consultant and a third-party testing laboratory, the processing plant will be responsible for implementing interventions recommended by the consultant to identify and eradicate the problematic strain. The intervention with the least amount of labor but the most expensive implementation costs is (iv) the addition of temperature sensors to half-gallon packaging.

**Price Premium Data**

Retail prices and product information for a sample of half-gallon milk products (n = 54) were collected in-store and online in September 2020 from Stop and Shop.

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**Table 2. Estimated costs of interventions for a 6,000 sq ft (557 m²) plant with 6–7 production lines and 25 drains in total**

<table>
<thead>
<tr>
<th>Intervention</th>
<th>Key costs considered</th>
<th>Low end ($)</th>
<th>Mean ($)</th>
<th>High end ($)</th>
<th>Sample size</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) Seek and destroy</td>
<td>1. Total cost for consultant for designated time period 2. Total cost for current sponge sampling and laboratory testing costs 3. Total cost for vector sampling and laboratory testing costs 4. Total cost for subtyping and identifying problematic isolate</td>
<td>2,000</td>
<td>12,500</td>
<td>137,500</td>
<td>n = 4</td>
</tr>
<tr>
<td>(ii) Improved preventative maintenance (PM) procedures</td>
<td>1. Current material costs for equipment part replacement (e.g., O-rings, gaskets, mesh screens, rubber fittings) 2. Labor costs 3. Downtime</td>
<td>56,667</td>
<td>80,000</td>
<td>125,000</td>
<td>n = 3</td>
</tr>
<tr>
<td>(iv) Addition of temperature sensor to half-gallon packaging</td>
<td>1. Material costs for time-temperature indicators for 25,150,781 containers per year</td>
<td>754,523</td>
<td>23,641,734</td>
<td>47,283,469</td>
<td>n = 5</td>
</tr>
<tr>
<td>(v) Application of antimicrobial coating to floor drains</td>
<td>1. Cost of coating for floors ($/sq ft) 2. Downtime required 3. Time required between reapplication of new coating</td>
<td>68,000</td>
<td>85,400</td>
<td>91,500</td>
<td>n = 3</td>
</tr>
</tbody>
</table>

1Sample size refers to the number of experts that provided cost estimates.
In addition to retail prices, we collected product information on organic status, milk fat percentage, and pasteurization method (Table 3). The sample of milk products had the following qualities: organic (n = 33) or conventional (n = 21); 2% reduced-fat (n = 17), 1% low-fat (n = 11), whole milk (n = 16), or fat-free (n = 10); and ultra-pasteurized (UP; n = 25) or high temperature, short time (HTST; n = 29). For analysis, we use the different fluid heat treatment processes to proxy shelf life (Chapman et al., 2001): the shelf life of UP milk and HTST milk was assumed to be 90 d and 21d, respectively.

### Environmental Benefit Data

The amount of milk consumed per capita, including milk consumers and nonmilk consumers, is 141 pounds (64 kg) each year (USDA 2020), which equates to approximately 5.70 fluid oz (0.17 L) per day. In the United States, dairy is the primary source of protein for 58% of households (Statista, 2018). Thus, the amount of milk consumed per capita for consumers who get most their daily protein from milk (i.e., milk consumers) was assumed to be approximately 9.82 fluid oz per day. The average global greenhouse gas emission for milk including production, processing, and transport has been estimated to be 2.4 kg of CO₂e per kg of milk (FAO, 2010), which amounts to 0.000725 t of CO₂e per 9.82 fluid oz (0.29 L) per day.

To determine the social benefit of each intervention strategy, we used the cost figure developed by the Interagency Working Group, which based the social cost of carbon values from 3 integrated assessment models at discount rates of 2.5, 3, and 5% (IWG, 2016). The social cost of CO₂ in 2020 using the 2.5, 3, and 5% discount rate was estimated as $62, $42, and $12 of 2007 dollars per metric ton of CO₂, respectively (EPA, 2016). Thus, using the previously calculated greenhouse gas emissions for milk per day (i.e., 0.000725 t of CO₂e per 9.82 fluid oz per day), the per capita social benefit of reduced CO₂e from potential avoided waste associated with an additional day of shelf life for fluid milk, using the 2.5, 3, and 5% discount rate, is $0.04, $0.03, and $0.01, respectively. These figures were ultimately used to determine the social benefit of implementing each of the 5 interventions.

### Empirical Methodology

The empirical methodology is divided into 3 sections: (i) shelf-life estimation, (ii) hedonic price regressions, and (iii) cost-benefit analysis. First, we estimated changes in shelf life attributed to each intervention. Then we estimated price premiums for an additional day of shelf life. Lastly, we used results from (i) and (ii) with the environmental benefit data to evaluate the overall cost effectiveness of each intervention strategy.

#### Shelf-Life Estimation

The shelf-life estimation when applying each intervention is based on the previously developed microbial spoilage model in Lau et al. (2022a), which predicts the spoilage of fluid milk by psychrotolerant gram-negative bacteria introduced as postpasteurization contamination. This model used the percentage of half-gallons that reached a microbial threshold that ensures compliance with the US Pasteurized Milk Ordinance limits for pasteurized milk (20,000 cfu/mL) by d 7 in the baseline model to estimate the shelf-life extension for each of the 5 interventions. In the model, 33.94% of half-gallons reached this threshold on d 7 and thus, each intervention was evaluated relative to this to determine the amount of storage time to reach a point where 33.94% of containers have >20,000 cfu/mL. More details on other aspects of the model parameterization are detailed in Lau et al. (2022a).

#### Price Regressions

Hedonic pricing models have a long history and were first introduced by Rosen (1974), who postulated that the monetary value of a product is derived from the specific prices associated with each of its attributes. This method has been used to determine agricultural land value (e.g., Bastian et al., 2002; Snyder et al.,

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**Table 3. Milk price summary statistics**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>n = 541</th>
</tr>
</thead>
<tbody>
<tr>
<td>Format</td>
<td></td>
</tr>
<tr>
<td>In-store</td>
<td>23 (43%)</td>
</tr>
<tr>
<td>Online</td>
<td>31 (57%)</td>
</tr>
<tr>
<td>Store</td>
<td></td>
</tr>
<tr>
<td>Stop &amp; Shop</td>
<td>16 (30%)</td>
</tr>
<tr>
<td>Wegmans</td>
<td>17 (31%)</td>
</tr>
<tr>
<td>Key Food</td>
<td>14 (26%)</td>
</tr>
<tr>
<td>Acme</td>
<td>7 (13%)</td>
</tr>
<tr>
<td>Type</td>
<td></td>
</tr>
<tr>
<td>Conventional</td>
<td>21 (39%)</td>
</tr>
<tr>
<td>Organic</td>
<td>33 (61%)</td>
</tr>
<tr>
<td>Product</td>
<td></td>
</tr>
<tr>
<td>1% Low-fat milk</td>
<td>11 (20%)</td>
</tr>
<tr>
<td>2% Reduced-fat milk</td>
<td>17 (31%)</td>
</tr>
<tr>
<td>Fat-free milk</td>
<td>10 (19%)</td>
</tr>
<tr>
<td>Whole milk</td>
<td>16 (30%)</td>
</tr>
<tr>
<td>Processing</td>
<td></td>
</tr>
<tr>
<td>High temperature short time</td>
<td>29 (54%)</td>
</tr>
<tr>
<td>Ultra-pasteurized</td>
<td>25 (46%)</td>
</tr>
<tr>
<td>Mean price (SD)</td>
<td>4.09 (1.37)</td>
</tr>
</tbody>
</table>
2007) and to study the price structure of various agricultural products such as eggs or rice (Chang et al., 2010; Ndindeng et al., 2021). Because products are differentiated by their characteristics, Rosen’s (1974) approach allowed us to parse out the value of each product attribute. In this study, we used the hedonic pricing approach to determine the value of attributes associated with fluid milk.

Using the price premium data (Table 3), we specified 5 linear hedonic models of increasing complexity to estimate the value of each product attribute commonly associated with fluid milk. The interactions and variables we considered for the cost of fluid milk included market channel of the product (i.e., online or in-store), production type (i.e., organic or conventional), milk fat (i.e., whole milk, fat-free milk, 1% low-fat, and 2% reduced-fat), and processing (i.e., HTST or ultrapasteurization). Shelf life was proxied by the processing attribute, but we also estimated models that included shelf-life values directly as a numeric variable.

The model was determined by the following equation:

$$P = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_5 x_5 + \varepsilon,$$  \[1\]

where $P$ is the observed retail price of fluid milk, $B_0$ is the intercept, $x_1$ to $x_5$ are the previously described milk product attributes, and $\varepsilon$ is a normally distributed error term. We estimated 5 different specifications of Equation [1] using Ordinary Least Squares regression. For each model, $B_0$ represents the reference product level of 1% conventional, low-fat milk, purchased in-store. With model 1, simple linear regression was used to test if shelf life significantly predicted the price with $x_1$ representing the numeric shelf-life variable. With each model, we included additional interaction terms to determine the value of those attributes to parse out the true value of shelf life. With model 2, $x_2$ is the online channel dummy variable to evaluate a possible change in the value of shelf life with the addition of online versus in-store channel attribute. With model 3, $x_3$ is the organic dummy variable to control for the difference in price between organic and conventional fluid milk. In model 4, we excluded the numeric shelf-life variable ($x_1$) and used $x_3$ as a dummy variable for UP processing. We then calculated the value of an additional day of shelf life by dividing the coefficient estimate $\beta_1$ by 69, the difference in days between the shelf life of HTST milk (i.e., 21 d) and UP milk (i.e., 90 d). To assess the value of 2% reduced-fat, fat-free, and whole milk attributes, we included $x_5$ as a milk fat factor variable in model 5. Similar to model 4, in model 5 we used the coefficient estimate for UP dummy variable to determine the value of shelf life.

Cost-Benefit Analysis

The costs considered in this analysis are described in the intervention cost data (Table 2). Both the private (firm) and social (environmental) benefits were considered in the analysis (Table 4). The private benefit is the value of each additional day of shelf life calculated previously with the hedonic price regression. The environmental benefit is the social cost of carbon for each additional day of shelf life. For interventions (i)–(iii), we estimated a range for the additional days of shelf life each intervention provided (depending on the level of implementation; see Table 4) and thus we calculated a lower and upper bound for the benefits and costs of these interventions. To calculate the net benefit of each intervention, we took 2 approaches; one approach only considered the private benefit of implementing the intervention, and the second approach accounted for both the private and social benefit of implementing the intervention. For the first approach, we subtracted the cost of implementing the intervention from the private benefit. For the second approach, we added the private and social benefits together and subtracted the cost of the intervention.

RESULTS AND DISCUSSION

Estimation of Fluid Milk Shelf-Life Extension That May Be Achieved by Different Interventions

The 5 interventions evaluated here were predicted to extend fluid shelf life by between 1 and 7 d (Table 4). The 2 interventions that were predicted to allow for the largest shelf-life extension were intervention (ii), improved PM, and intervention (iii), increase PEC. The other 3 interventions (i, iv, and v; see Table 4) were estimated to only allow for 1–2 d of shelf-life extension. For intervention (ii), the range of shelf-life extension varied substantially (2–7 d), based on the estimated effectiveness, which was 1 log$_{10}$ reduction and 3 log$_{10}$ reduction for the 2 levels of this interventions that were modeled. Our results further support previous studies that suggested that feasible interventions for extending fluid milk shelf life include regularly scheduled PM interventions or improving sanitary equipment and plant design (Reichler et al., 2020; Murphy et al., 2021). In addition to our work here, Buehler et al. (2018) previously evaluated different practical interventions to extend the shelf life of milk, focusing however on shelf-life issues due to growth of sporeforming bacteria introduced with raw milk; in this previous study the developed model predicted that adjusting the temperature storage from 6°C to 4°C extended average shelf life by 9 d. Although that study and our study reported here
together suggest that substantial shelf-life extension of HTST milk is possible, future development of models that simultaneously simulate the effect of microbial raw milk quality and postpasteurization contamination are needed to further facilitate industry decision making.

Although one may argue that the estimated shelf-life extension for some interventions (e.g., those estimated to only yield extensions of 1–2 d) are small and may have minimal practical value, one must be aware that managing perishable items compared with items that have longer shelf life poses a different challenge. With perishable items such as fluid milk, which has an average of 17 d of shelf life, an additional 1 d of shelf life (e.g., from an intervention such as an application of antimicrobial coating to the floor drains) can still provide a substantial value to a firm. From a supply chain management perspective, extension of shelf life allows for reduction in production and delivery lead times and can increase the stability of supply logistics (Cavaliere and Ventura, 2018; Akkas and Gaur, 2022). For consumers, products with a longer shelf life would add a convenience attribute by allowing for fewer trips to the supermarket. Unlike other perishable products, consumers cannot use appearance as an extrinsic cue to evaluate the intrinsic quality of fluid milk (Aschemann-Witzel et al., 2015) and thus must rely on the printed best-by date. Therefore, the ability to apply the interventions that extend shelf life for 1 to 7 d may offer substantial benefits.

**Estimation of Price Premiums for Fluid Milk with Extended Shelf Life**

When retailers are purchasing perishable goods such as fluid milk from suppliers or when consumers are purchasing product from a retail store, they must consider the likelihood that the product will spoil before it is fully consumed; thus, there is a value associated with each day of shelf life. To assess this value (and hence the value of fluid milk shelf-life extension), we estimated price premium regressions. Fluid milk price data collected for this effort included more organic half-gallon samples (61%) than conventional half-gallon samples (39%). The sample of half-gallon milk products were roughly evenly distributed between HTST (54%) and UP processing (46%) and between in-store (43%) and online channel (57%). On average the price of the half-gallon samples was $4.09 (SD = $1.37). Using these data, we used 5 models to determine the value of shelf life, each with increased complexity to test the robustness and stability of our estimates. From these models, the coefficient estimates for the shelf-life variable and UP variable were used to determine the value of shelf life. model 1 to 3 suggests that the value of shelf life

### Table 4. Total benefits and costs per half-gallon of fluid milk

<table>
<thead>
<tr>
<th>Intervention</th>
<th>Days of extra shelf-life</th>
<th>Private benefit per 1/2 gallon1 ($)</th>
<th>Social benefit per 1/2 gallon2 ($)</th>
<th>Cost of intervention3 ($)</th>
<th>Net private gain per 1/2 gallon (private benefit − cost of intervention) ($)</th>
<th>Net private and social gain per 1/2 gallon (private + social benefit − cost of intervention) ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) Seek and destroy</td>
<td>1–2</td>
<td>0.03–0.06</td>
<td>0.02–0.04</td>
<td>0.00008–0.00014</td>
<td>0.02–0.06</td>
<td>0.04–0.09</td>
</tr>
<tr>
<td>(ii) Improved preventative maintenance (PM) procedures</td>
<td>2–7</td>
<td>0.06–0.20</td>
<td>0.04–0.13</td>
<td>0.00022–0.00047</td>
<td>0.05–0.19</td>
<td>0.09–0.33</td>
</tr>
<tr>
<td>(iii) Increase periodic equipment cleaning (PEC)</td>
<td>6–7</td>
<td>0.17–0.20</td>
<td>0.12–0.13</td>
<td>0.00012–0.00029</td>
<td>0.17–0.19</td>
<td>0.28–0.33</td>
</tr>
<tr>
<td>(iv) Addition of temperature sensor to half-gallon packaging</td>
<td>2</td>
<td>0.06</td>
<td>0.04</td>
<td>0.00171</td>
<td>0.05–0.19</td>
<td>0.09–0.33</td>
</tr>
<tr>
<td>(v) Application of antimicrobial coating to floor drains</td>
<td>1</td>
<td>0.03</td>
<td>0.02</td>
<td>0.00270–0.00364</td>
<td>0.02–0.03</td>
<td>0.04</td>
</tr>
</tbody>
</table>

1The value of each additional day of shelf-life was assumed to be $0.03 per 1/2 gallon; this was based on the hedonic pricing approach detailed in the manuscript.
2The social cost of CO2e for each additional day of shelf-life using the discount rate of 3%.
3The estimated cost of implementing each intervention strategy using expert elicitation and supplier quotes (see Table 2 for details).
is $0.03 per day (Table 5). For models 4 to 5, the estimated coefficient for the UP milk indicator represents the total value of an additional 69 d of shelf life. By dividing the value of UP milk processing over 69 d, we also estimated the value of shelf life to be $0.03 per day. The robustness of our estimated value for an added day of shelf life across each of the 5 specifications indicates that our main results are not model-dependent. In addition, the estimated value of $0.03 for each additional day of fluid milk shelf life is similar in magnitude to the estimates from several other studies. Tsiros and Heilman (2005) used a mixed effect model to investigate willingness to pay for milk as the number of days left before the product’s expiration decreases and estimated willingness to pay of $0.04 per day. Paterson and Clark (2020) conducted laboratory-based auctions to assess the value of half-gallons of milk with close (near-end) and far-out (fresh) code dates, and the mean margins when consumers bid on products after viewing the packaging equated to just over $0.02 per day.

Our data on the value of shelf-life extension of HTST milk are important as dairy products represent a unique challenge within grocery stores because they have logistical requirements such as temperature control and a perishable nature and therefore must be purchased frequently (Reiner et al., 2013). In addition to its unique challenges, we found no direct alternatives to HTST fluid milk from a sensory profile, either. Even though consumers can opt to buy milk with different processing technologies such as UP milk for extended shelf life, an important criterion affecting consumer acceptance is flavor (Kühn et al., 2006). Because UP milks are processed at a higher temperature compared with HTST milks, UP milks have a distinct cooked and sulfur flavor profile which may not be favorable to some consumers (Lee et al., 2017; Jo et al., 2018). Data on the value of extended shelf life of HTST milk will thus help industry with decision making on the economic value of further development of extended shelf-life HTST fluid milk products.

Markdown management is widely studied in retailing, and some research suggests markdowns as a recommended tactic to increase sales and prevent products from becoming unsaleable (GMA-FMI, 2008). However, even though applying a discount may be a strategy to promote the sale of aging products, this is generally untenable for products that already have a low margin such as milk. Offering a discount can result in a new pool of customers who only want the old product and can cause an increase in ordering from the retail store (Chua et al., 2017). In addition, determining the optimal discounting for products would require a large investment from retailers (e.g., analysis of profit margins for each product, evaluation of the effect of discounting on the specific product, cross category effects, and so on; Wang and Li, 2012). Discounting milk can also be detrimental because there have been numerous studies showing that the price of a product serves as an indicator of quality perception for consumers (e.g., Monroe, 1973; Gneezy et al., 2014), and consumers’ quality perception of the product decreases with markdown (Hariss et al., 2020). Thus, discounting may not be a profitable strategy for products similar to milk, whereas extending the shelf life of products may be a better solution that allows the firm to maintain the full value of the product for a longer period of time.

### Cost-Benefit Analysis for Different Interventions That Increase Fluid Milk Shelf Life

The private and social benefits for 4 of the 5 interventions (i.e., interventions i, ii, iii, and v) evaluated here

---

**Table 5. Price regressions**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Model 1&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Model 2&lt;sup&gt;2&lt;/sup&gt;</th>
<th>Model 3&lt;sup&gt;3&lt;/sup&gt;</th>
<th>Model 4&lt;sup&gt;4&lt;/sup&gt;</th>
<th>Model 5&lt;sup&gt;5&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B&lt;sup&gt;6&lt;/sup&gt;</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>SE</td>
<td>SE</td>
<td>SE</td>
<td>SE</td>
</tr>
<tr>
<td>1% Low-fat milk</td>
<td>2.30 0.18</td>
<td>2.05 0.22</td>
<td>1.98 0.22</td>
<td>2.57 0.20</td>
<td>2.50 0.27</td>
</tr>
<tr>
<td>Shelf-life</td>
<td>0.03 0.00</td>
<td>0.03 0.00</td>
<td>0.03 0.00</td>
<td>0.41 0.19</td>
<td>0.41 0.19</td>
</tr>
<tr>
<td>Online</td>
<td></td>
<td>0.35 0.19</td>
<td></td>
<td>0.61 0.28</td>
<td>0.61 0.28</td>
</tr>
<tr>
<td>Organic</td>
<td></td>
<td></td>
<td></td>
<td>1.96 0.27</td>
<td>1.93 0.28</td>
</tr>
<tr>
<td>Ultra-pasteurized</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.17 0.27</td>
</tr>
<tr>
<td>2% Reduced-fat milk</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.06 0.30</td>
</tr>
<tr>
<td>Fat-free milk</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.10 0.27</td>
</tr>
<tr>
<td>Whole milk</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>1</sup>Simple linear regression with the intercept representing a 1% conventional, low-fat milk purchase in-store with a numeric shelf-life variable.

<sup>2</sup>Model 2 represents model 1 with the addition of an online channel dummy variable.

<sup>3</sup>Model 3 represents model 2 with the addition of an organic dummy variable.

<sup>4</sup>Model 4 represents model 3 with the exclusion of the shelf-life variable and the addition of a dummy variable for ultra-pasteurized processing.

<sup>5</sup>Model 5 represents model 4 with the addition of milk fat variable.

<sup>6</sup>B is the unstandardized beta; it represents the slope of the line between the predictor variable and the dependent variable.
were consistently estimated with a positive net gain when considering either only private benefits (range of $0.02–0.19 per half-gallon; see Table 4) or both private and social benefits (range of $0.04–0.33 per half-gallon; see Table 4). Interventions (ii), improving PM procedures, and (iii), increased PEC, which both provided for substantial shelf-life extensions (2–7 d), showed the largest effect on net private gain ($0.05 to 0.19 and $0.17–0.19, respectively), and net private and social gain ($0.09 to 0.33 and $0.28–0.33, respectively). The estimates for total cost of implementing intervention (ii) ranged from $56,667 to $125,000, resulting in a cost of $0.00225 to $0.00497 per half-gallon, whereas the estimates for total cost of implementing intervention (iii) ranged from $25,667 to $50,000, which equates to between $0.00102 and $0.00199 per half-gallon of milk.

Interventions (i), implementing seek and destroy, and (v), application of antimicrobial coating to floor drains, had lower estimated net private gain ($0.02 to 0.06 and $0.02–0.03, respectively) and net private and social gains ($0.04 to 0.09 and $0.04, respectively). The total costs of implementing intervention (i) were estimated to be between $2,000 and $137,500. This was treated as an annual cost (as it is likely that this would have to be repeated yearly as new issues that need to be addressed with seek and destroy are expected to occur at some frequency, which we assumed to be annual); this cost equates to between $0.00008 and $0.00547 per half-gallon. The total costs of implementing intervention (v) were estimated to be between $68,000 and $91,500, which equates to between $0.00270 and 0.00364 per half-gallon.

Intervention (iv), the addition of temperature sensor to half-gallon packaging, was estimated to be the least cost-effective measure with net private gain estimates ranging from −$1.82 to +$0.03, net private and social gain estimates ranging from −$1.79 to +$0.06 and estimated costs ranging from $0.03 and $1.88 per half-gallon (Table 4). Of the 5 suppliers that were contacted for a quote on the temperature sensors, only one supplier provided a price (i.e., $0.03 per sensor) that would allow for a positive net gain. As a result, when implementing this intervention, we estimated a net loss per half-gallon of milk when looking at the high end of the potential costs. These data suggest that reliable low-cost sensors would be needed before this intervention is competitive for fluid milk shelf-life extension.

Overall, our data suggest that several interventions that can increase fluid milk shelf life will result in a net gain when considering either only private or both private and social benefits, assuming that a price premium of $0.03 per half-gallon of milk can be realized and that our cost estimates are appropriate. Given that consumers value shelf life in fluid milk products, it seems likely that there would be an opportunity to pass at least some of the costs for implementing these interventions on to consumers through retail pricing in stores, even if the full $0.03 premium may not be possible. While milk is currently differentiated based on milk fat percentage, price, and conventional versus organic, this provides an opportunity for firms to use the shelf-life attribute to compete in vertical product differentiation. Grebitus et al. (2013) conducted a survey that showed that consumers were willing to pay for longer shelf life in ground beef as long as the product was safe, and they understood the technology. Cavaliere and Ventura (2018) furthermore showed that consumers will accept technology that extends shelf life if they have a high level of food knowledge. Montero et al. (2021) show that convenience-oriented consumers are willing to pay a premium for a ready to eat meal with an extended shelf life. Thus, consumers are receptive to paying more for a product with longer shelf life.

Fluid milk’s effect on food waste is substantial as this product makes up 31% of dairy products expenditure in US households in 2020 and was the sixth most consumed beverage in the United States in 2020 (Bureau of Labor Statistics 2021; Beverage Marketing Corporation 2020). Hence, extending the shelf life of fluid milk would not only provide significant benefits to firms but would also provide substantial environmental benefits. Environmental benefits of fluid milk shelf-life extension may be particularly valuable because there has been increasing industry attention and pressure to address the challenge of food waste. If a company could credibly signal that their milk products are more environmentally friendly, this type of information disclosure may further enhance product differentiation, relax price competition, and therefore allow firms to increase prices for the fluid milk (Shaked and Sutton, 1982). On the retail end, when product is not able to be sold, a large portion of the product is sent to landfills or an incinerator, which further increases air pollution and greenhouse gas emissions (Bloom, 2010). The environmental impact of food consumption is another significant consumer concern that ultimately shapes their food purchasing behavior (Moser, 2015). Corporate environmental, social, and governance (ESG) initiatives now shape consumer choice as well as institutional investment decisions (Kim et al., 2021). Companies are actively pursuing sustainability as a strategy to attract and retain their customer base and to remain competitive among other businesses (Du et al., 2007; Oláh et al., 2019). Consumers are interested in corporate social responsibility initiatives of companies, and their effect on the environment is one of the many factors they use to assess a company (Bhattacharya and Sen, 2004; Du et al., 2007; Rodrigues and Borges, 2015). Indeed, com-
companies that display an environmental orientation and a commitment to the environment are associated with greater profit and market share (Menguc and Ozanne, 2005).

**Study Limitations and Opportunities for Future Studies**

Although the cost-benefit analysis conducted here provides insights on the economic and environmental impact of various intervention strategies that could be used to extend fluid milk shelf life, we identified several limitations that should be addressed in future studies. One limitation of this analysis is the costs and benefits are based on predicted shelf-life extensions obtained with a spoilage simulation model and based on estimated costs. Another limitation is that the intervention cost estimates are based on a relatively small number of experts. For more reliable data, interventions would need to be performed (or at least piloted) in a processing plant (with appropriate cost accounting) to obtain “real world” data on intervention costs and the additional days of shelf life a given intervention can provide. However, use of previously developed shelf-life prediction models, including the model used here (Buehler et al., 2018; Lau et al., 2022a), along with the cost-benefit analysis conducted here, can facilitate plant-level decision making by enabling processors to perform an initial assessment of interventions most likely to be cost-effective. It is important, however, to recognize that implementation costs will vary depending on the processing plant size and a firm’s specific situation and that initial feasibility assessments may require different cost estimates than those used here.

Another limitation of the study reported here is that the implementation of the 5 interventions was evaluated independently, which helps processors make a choice between discrete interventions. However, we understand that processing plants may want to implement multiple interventions simultaneously. Evaluation of multiple interventions implemented simultaneously, however, presents significant challenges from a modeling standpoint, as some of these interventions (i.e., seek and destroy intervention and increased PEC intervention) change the same model input (frequency) in the model.

In addition, we identified several limitations in the evaluation of the value of shelf life worth noting. There were 2 assumptions made: (i) that the value of additional shelf life increased linearly between HTST and UP products and that (ii) the shelf life of the HTST and UP products are 21 d and 90 d, respectively. Also, the product information and prices collected for the evaluation of the value of shelf life were based on a convenience sample of New York retail stores and therefore may not be representative of all regions in the United States. While we believe that there are opportunities to further improve estimates on the value of added shelf life for HTST fluid milk, our estimates of an added value of $0.03 per half-gallon are in-line with previous estimates (Tsiros and Heilman, 2005; Paterson and Clark, 2020), as detailed above.

Lastly, even though we modeled a select few interventions that are relevant to fluid milk shelf-life extension, there is a growing body of research that examines the use of different interventions to improve the quality of perishable goods resulting in shelf-life extension. For example, strategies such as the use of high-pressure processing, pulsed light application and cold plasma-mediated treatments have been explored to extend the shelf life of perishable goods such as produce (Pan et al., 2019). Active packaging and modified atmosphere packaging are also interventions that have been used to extend the shelf life of products (Rodriguez-Aguilera and Oliveira, 2009). Whereas some available technologies may not be practically or economically feasible for fluid milk, the approaches used in our study can be used in future studies to evaluate different shelf-life extension strategies for a range of dairy products.

**CONCLUSIONS**

Despite the growing literature in operations and logistics management to tackle the logistical aspects of food waste, for certain food products a significant opportunity exists to address this problem through the intrinsic nature of the product. This study explored how interventions applied at a dairy processing plant can extend the shelf life of fluid milk, thereby reducing consumer-level food waste. Importantly, the types of interventions applied here were estimated to often provide both private and social benefits, suggesting that further work on improving the intrinsic nature of dairy products (e.g., shelf life) may substantially benefit the dairy industry, both from an individual firm profitability standpoint as well as from a reputational standpoint, with regard to the industry’s commitment to addressing food waste.

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at https://github.com/sl2763/CBADATA. No human or animal subjects were used, so this analysis did not require approval by an Institutional Animal Care and Use Committee or Institutional Review Board. The authors have not stated any conflicts of interest.

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