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# Simulation-Based Game Theoretical Analysis of Japanese Milk Supply Chain for Food Waste Reduction

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**Abstract.** The one-third rule, which sets tight wholesale and retail limits for food products, is arguably a primary cause of huge food waste in Japan. However, the effect of relaxing the limits was found to vary depending on some conditions. Thus, to further understand how these limits affect food wastage, we take a game-theoretical analysis approach. In this approach, we formulate a normal-form game played by a manufacturer and a retailer in a milk supply chain, develop a simulation model of the chain, and use the simulator to obtain sample values of the players' payoffs earned under every pair of their strategies. We then apply a statistical multiple comparison test to the data to identify the *statistical best responses* of a player to each opponent strategy, derive *statistical Nash equilibriums*, and compare the equilibriums obtained under different limits and consumers' preferences. Consequently, it is confirmed that relaxing the limits may undesirably impact food waste.

**Keywords:** Food Supply Chain, Food Waste, Normal-Form Game

## 1 Introduction

The Sustainable Development Goals (SDGs) adopted at the United Nations Summit in 2015 aim to reduce by half the per capita global food waste at the retail and consumer levels and the food losses along the production and supply chains [1]. Reportedly, about 25.31 million tons of food waste was caused in FY 2018 in Japan [2]. Further, the waste is estimated to include six million tons of food that were still edible, of which 3.24 million tons were generated from businesses, including the food manufacturing, wholesale, retail, and restaurant industry, and 2.76 million tons were generated from households. Thus, it is crucial to mitigate food waste across the whole supply chain [3][4].

It is argued that the one-third rule [5] is a primary cause of the significant food waste. This rule is a commercial custom that is widely followed in the Japanese food industry. It divides the time between production and expiration dates of a food product into three equal length intervals and sets the wholesale and retail limits of the food at the end of the first interval and the second interval, respectively. Such limits are

also imposed in some other countries; however, they tend to be more relaxed than those in Japan are. Furthermore, social experiments conducted in 2013 observed the effect of relaxing the wholesale limit to one-half to be bidirectional [6]. While, relaxing the limit reduced the amount of waste in some food categories, the waste caused by retailers in other categories slightly increased. This suggests the complexity of the relation between the limits and food waste, mediated by various decisions made by the different players in the food supply chain, such as manufacturers, wholesalers, retailers, and consumers. Therefore, deepening the understanding of the mechanism of how the limits affect food wastage is required to devise effective means for food waste reduction.

To address this challenge, we take a game-theoretical analysis approach in this paper. Since most supply chains are composed of several self-centered business entities, game theoretical models have become a standard approach for analyzing supply chains [7-9]. When using a game-theoretical model, we usually simplify the supply chain considerably to make it straightforward to calculate the payoffs that each player earns in the game. However, such simplification makes it difficult to investigate the complex mechanism that we are interested in, here. Thus, in this paper, we rely on the numerical simulation instead, to obtain sample values of the players' payoffs and utilize statistical techniques to analyze the data.

In the remainder of this paper, after introducing the supply chain simulation model and statistical game-theoretical analysis approach, we present numerical experiments, their results, and discuss their implications. Finally, we conclude this paper by providing some future research directions.

## 2 Supply Chain Simulation Model

### 2.1 Model Outline

Our milk supply chain model comprises a manufacturer, a retailer, and anonymous consumers. The manufacturer produces particular milk packages from raw milk and holds them in their warehouse. The retailer buys the packages from the manufacturer and takes them to their warehouse. They then move packages to their shelf and sell them to consumers. The number of consumers visiting the retailer each day  $d$  is a random variable following a normal distribution  $n_d \sim N(\bar{n}, \sigma_n^2)$  ( $= N(100, 100)$  in the numerical experiments below). Each consumer may choose a candidate package on the shelf and buy it or leave the store without buying the milk package. This decision is affected by the remaining days to expiration and the price of the milk packages on the shelf. That is, they prefer fresher and cheaper milk packages.

The time to expiration of the milk packages is  $L^C$  days, including the date of production as the first day ( $L^C = 12$  in the numerical experiments). Thus, if the one-third rule is applied, the wholesale limit  $L^M$  and the retail limit  $L^R$  are set at  $\lceil L^C/3 \rceil$ th day and  $\lceil 2 \cdot L^C/3 \rceil$ th day respectively ( $L^M = 4, L^R = 8$ ). Otherwise, both are regarded as equal to  $L^C$  ( $L^M = L^R = 12$ ).

The number of milk packages whose *days-from-production* (DFP) is  $\delta$  held in the manufacturer's warehouse is denoted by  $s_\delta^M$ , and the total number of packages in the

warehouse is given by  $s^M = \sum_{\delta} s_{\delta}^M$ . This inventory is controlled by determining the production order quantity  $o_d^M$  placed on day  $d$  according to a standard periodical ordering policy. A fixed lead time  $lt^M (= 1)$  is necessary between planning and completing production. Raw milk is assumed to be always available as much as required at a fixed cost per unit. Its storage is outside the scope of the model, and no other costs related to production are considered.

The numbers of milk packages whose DFP is  $\delta$  held in the retailer's warehouse and on-shelf are denoted by  $s_{\delta}^R$  and  $s_{\delta}^S$ , respectively, and the total numbers of packages in the warehouse and on the shelf are given by  $s^R = \sum_{\delta} s_{\delta}^R$  and  $s^S = \sum_{\delta} s_{\delta}^S$ , respectively. The total inventory of the retailer  $s^R + s^S$  is controlled by determining the purchase order quantity  $o_d^R$  placed on day  $d$  according to a standard periodical ordering policy. A fixed lead time  $lt^R (= 1)$  is necessary between placing an order and replenishment. The capacity of the shelf is limited to  $c^S (= 50)$ ; no capacity limit is imposed on the warehouses of the manufacturer and the retailer.

## 2.2 Operational Flow of Manufacturer

At the beginning of each day  $d$ , the manufacturer determines the order quantity:

$$o_d^M = \sum_{t=d-lt^R}^{d-1} o_t^R + b_{d-1}^R + (lt^M - lt^R + 2) \cdot \bar{n} - \sum_{t=d-lt^M}^{d-1} o_t^M - s^M + ss^M \quad (1)$$

where  $b_{d-1}^R$  specifies the number of stockout milk packages remaining unshipped on the day before, and  $ss^M$  denotes the safety stock level:

$$ss^M = k^M \cdot \sqrt{\max(0, lt^M - lt^R + 2) \cdot \sigma_n} \quad (2)$$

where  $k^M$  is the manufacturer's safety stock coefficient.

Then, it ships out milk packages to the retailer. The total number to be shipped is:

$$f_d^M = \min(s^M, o_{d-lt^R}^R + b_{d-1}^R) \quad (3)$$

The manufacturer chooses the order in which the packages are shipped between FIFO (from old to new) or LIFO (from new to old). In the case of FIFO, the number of milk packages shipped whose DFP is  $\delta$  is given recursively by:

$$f_{d,\delta}^M = \min(s_{\delta}^M, f_d^M - \sum_{\tau=\delta+1}^{L^M} f_{d,\tau}^M) \quad (\delta = L^M, L^M - 1, \dots) \quad (4)$$

Otherwise, it is given by:

$$f_{d,\delta}^M = \min(s_{\delta}^M, f_d^M - \sum_{\tau=1}^{\delta-1} f_{d,\tau}^M) \quad (\delta = 1, 2, \dots) \quad (5)$$

After shipping out, the manufacturer's inventory is updated as  $s_{\delta}^M = s_{\delta}^M - f_{d,\delta}^M (\forall \delta)$  and the stockout is given by  $b_d^R = o_{d-lt^R}^R + b_{d-1}^R - f_d^M$ .

When the production of the day is completed, the produced milk packages are replenished in the warehouse as  $s_1^M = o_{d-lt^M}^M$ .

At the end of the day, the milk packages whose DFP has reached the limit  $L^M$  are wasted as  $(w_d^M, s_{L^M}^M) = (s_{L^M}^M, 0)$ .

where  $w_d^M$  is the number of milk packages wasted by the manufacturer on day  $d$ . Further, the reward of the manufacturer is updated:

$$r^M = r^M + \sum_{\delta=1}^{L^M} p_{\delta}^R \cdot f_{d,\delta}^M - p^M \cdot s_1^M - p^B \cdot b_d^R - p^W \cdot w_d^M \quad (6)$$

where  $p_{\delta}^R$  is the wholesale price of a milk package whose DFP is  $\delta$ ,  $p^M$  ( $= 100$ ) is the unitary price of raw milk, and  $p^B$  ( $= 5$ ) and  $p^W$  ( $= 0$ ) are the penalty of stockout and wastage, respectively. The wholesale price is given by:

$$p_{\delta}^R = 150 - \Delta^M (\delta - 1) \quad (7)$$

where  $\Delta^M$  is the discount rate of the wholesale price determined by the manufacturer.

Finally, when the next day starts, the DFP of the milk packages in the warehouse is updated:

$$s_{\delta}^M = \begin{cases} 0 & (\delta = 1) \\ s_{\delta-1}^M & (1 < \delta \leq L^M) \end{cases} \quad (8)$$

### 2.3 Operational Flow of Retailer

At the beginning of each day  $d$ , the retailer determines the order quantity:

$$o_d^R = (lt^R + 2) \cdot \bar{n} - \sum_{t=d-lt^R}^{d-1} o_t^R - b_{d-1}^R - s^R - s^S + ss^R \quad (9)$$

where  $ss^R$  denotes the safety stock level:

$$ss^R = k^R \cdot \sqrt{lt^R + 2} \cdot \sigma_n \quad (10)$$

where  $k^R$  is the retailer's safety stock coefficient.

At the beginning of the day as well as, at most, twice during the day when  $s^S$  reaches the ordering point  $op$  ( $= 10$ ), the retailer moves milk packages from the warehouse to the shelf. The number of packages to be moved at  $i$  ( $\leq 3$ ) th occasion of day  $d$  is given by:

$$f_{d,i}^R = \min(s^R, c^S - s^S) \quad (11)$$

The retailer chooses the order in which the packages are moved between FIFO or LIFO. In the case of FIFO, the number of milk packages moved on this occasion whose DFP is  $\delta$  is given recursively by:

$$f_{d,i,\delta}^R = \min\left(s_{\delta}^R, f_{d,i}^R - \sum_{\tau=\delta+1}^{L^R} f_{d,i,\tau}^R\right) \quad (\delta = L^R, L^R - 1, \dots) \quad (12)$$

Otherwise, it is given by:

$$f_{d,i,\delta}^R = \min\left(s_{\delta}^R, f_{d,i}^R - \sum_{\tau=1}^{\delta-1} f_{d,i,\tau}^R\right) \quad (\delta = 1, 2, \dots) \quad (13)$$

After moving them to the shelf, the retailer's inventory is updated:

$$(s_{\delta}^R, s_{\delta}^S) = (s_{\delta}^R - f_{d,i,\delta}^R, s_{\delta}^S + f_{d,i,\delta}^R) \quad (\forall \delta) \quad (14)$$

The number of milk packages on the shelf  $s_{\delta}^S$  decreases when a consumer buys one.

At the end of the day, the packages shipped from the manufacturer arrive, and they are replenished in the warehouse as  $s_\delta^R = s_\delta^R + f_{d,\delta}^M (\forall \delta)$ . Then, the milk packages whose DFP has reached the limit  $L^R$  are wasted as  $(w_d^R, s_{L^R}^R, s_{L^R}^S) = (s_{L^R}^R + s_{L^R}^S, 0, 0)$ , where  $w_d^R$  is the number of milk packages wasted by the retailer on day  $d$ . Further, the reward of the retailer is updated:

$$r^R = r^R + \sum_{\delta=1}^{L^R} p_\delta^S \cdot f_{d,\delta}^S + p^B \cdot b_d^R - \sum_{\delta=1}^{L^M} p_\delta^R \cdot f_{d,\delta}^M - p^W \cdot w_d^R \quad (15)$$

where  $f_{d,\delta}^S$  is the number of milk packages, whose DFP is  $\delta$ , sold to consumers on day  $d$ , and  $p_\delta^S$  is the retail price of those packages:

$$p_\delta^S = 200 - \Delta^R (\delta - 1) \quad (16)$$

where  $\Delta^R$  is the discount rate of the retail price determined by the retailer.

Finally, when the next day starts, the DFP of the milk packages in the warehouse and on the shelf is updated:

$$(s_\delta^R, s_\delta^S) = \begin{cases} (0, 0) & (\delta = 1) \\ (s_{\delta-1}^R, s_{\delta-1}^S) & (1 < \delta \leq L^R) \end{cases} \quad (17)$$

## 2.4 Consumers' Behavior

The number of milk packages  $f_{d,\delta}^S$  bought by consumers each day  $d$  is determined by their behavior. On day  $d$ , in total,  $n_d$  consumers arrive at the store one by one. Each first chooses a candidate milk ('s DFP  $\delta$ ) if the shelf is not empty ( $\{\delta | s_\delta^S > 0\} \equiv D \neq \emptyset$ ) when they arrive at the store. If the shelf is empty ( $D = \emptyset$ ), they leave the store without buying a package. This decision is made according to the nested logit choice model [10], whose first step specifies the probability of choosing  $\delta$ :

$$prob_1(\delta) = \frac{\exp(u_\delta)}{\sum_{\tau \in D} \exp(u_\tau)} \quad (18)$$

where  $u_\delta$  specifies the utility of buying a milk package of  $\delta$ :

$$u_\delta = 0.6789 \cdot (12 - \delta) + 0.1356 \cdot (200 - p_\delta^S) \quad (19)$$

The values of the utility model's coefficients are determined according to a conjoint analysis study conducted earlier in Japan [11]. Then, the second step decides whether they buy the candidate milk or not according to:

$$prob_2(\delta) = \frac{\exp(u_\delta)}{\exp(u_\delta) + \exp(u_\emptyset)} \quad (20)$$

where  $u_\emptyset$  denotes the utility of buying no milk, which is assumed to be:

$$u_\emptyset = 0.6789 \cdot (12 - \delta_\emptyset) \quad (21)$$

In this equation,  $\delta_\emptyset$  can be regarded as a parameter expressing the consumers' preference for freshness. The higher this value, the looser the preference.

### 3 Statistical Game Theoretical Analysis

The performance of the supply chain is determined by a strategic interaction between the manufacturer and retailer. We capture this interaction as a normal-form game.

The set of the manufacturer's strategy is given by  $A^M = \{FRL, FRH, FDL, FDH, LRL, LRH, LDL, LDH\}$ . The first alphabet specifies whether the shipping order is FIFO ( $F$ ) or LIFO ( $L$ ), which we expect to be a primary determinant of food waste. The second shows whether old milk packages are discounted, which may have an interaction with the shipping order. Regular price policy ( $R$ ) does not discount old packages ( $\Delta^M = 0$ ), and discounted price policy ( $D$ ) discounts them ( $\Delta^M = 3$ ). The last one concerns the safety stock level, which will also affect food waste. Low level ( $L$ ) sets the service level at 90% ( $k^M = 1.29$ ), and high level ( $H$ ) sets it at 99% ( $k^M = 2.33$ ).

Similarly, the set of the retailer's strategy is given by  $A^R = \{FRL, FRH, FDL, FDH, LRL, LRH, LDL, LDH\}$ . The first alphabet denotes whether milk packages are moved from the warehouse to the shelf in FIFO ( $F$ ) or LIFO ( $L$ ), which we envisage as another determinant of food waste. The second specifies the pricing policy. In the case of  $R$ , old packages are not discounted ( $\Delta^R = 0$ ), and  $L$ , they are discounted so that they should seem approximately equally preferable to consumers as a new one ( $\Delta^R = 4$ ). The last is the safety stock policy.  $L$  sets the service level at 90% ( $k^R = 1.29$ ), and  $H$  sets it at 99% ( $k^R = 2.33$ ).

Since the payoff matrix is not given a priori, we derive the equilibriums of this game using the supply chain simulation model introduced above and a statistical technique. Specifically, we follow the steps below to identify the equilibriums.

**Step 1:** If all the strategy pairs in  $A^M \otimes A^R$  have been investigated, go to **Step 3**. Otherwise, choose a strategy pair to investigate next and move to **Step 2**.

**Step 2:** Run the simulation model 10 times under the specified strategy pair for 365 days (after 100 days of dry run) and obtain 10 sample values of the two players' rewards. Go back to **Step 1**.

**Step 3:** Apply a statistical multiple comparison test to the data of sample reward values obtained by each of the eight strategies of one player against the other and identify the *statistical best responses* of the former player to each strategy of the latter.

**Step 4:** Identify *statistical Nash equilibriums*, the set of strategy pairs that are *statistical best responses* to each other.

### 4 Numerical Experiments

We verify the proposed approach and assess the effect of the one-third rule on food waste and consumers' satisfaction by carrying out numerical experiments with and without the rule under different values of  $\delta_\phi$  ( $\in \{12, 8, 7\}$ ), a parameter representing the consumers' preference for freshness. **Fig. 1** shows the statistical Nash equilibriums obtained in each case. We can see that equilibriums depend on both whether the one-third rule is imposed and the consumers' preference ( $\delta_\phi$ ).



The amount of waste depends primarily on the shipping order policy of the manufacturer and secondarily on the moving order policy of the retailer. For reducing food waste, both are preferred to be FIFO. Interestingly, the results show that the one-third rule has an effect of eliminating equilibriums, including the LIFO policy of the manufacturer. It will positively impact food waste reduction. This effect may be because imposing the wholesale limit will make it unnecessary for the retailer to insist on the LIFO policy (of the manufacturer) to avoid buying very old milk packages. On the other hand, the one-third rule does not affect the retailer's moving order policy.

	FRL	FRH	FDL	FDH	LRL	LRH	LDL	LDH
FRL			★	★			★	
FRH			★	★			★	
FDL								
FDH								
LRL	★							
LRH								
LDL								
LDH								

(a) With the one-third rule &  $\delta_\theta = 7$ 

	FRL	FRH	FDL	FDH	LRL	LRH	LDL	LDH
FRL			★				★	
FRH			★				★	
FDL								
FDH								
LRL	★	★						
LRH	★	★						
LDL	★	★						
LDH		★						

(d) Without the one-third & and  $\delta_\theta = 7$ 

	FRL	FRH	FDL	FDH	LRL	LRH	LDL	LDH
FRL	★	★						
FRH	★							
FDL								
FDH								
LRL								
LRH								
LDL								
LDH								

(b) With the one-third rule &  $\delta_\theta = 8$ 

	FRL	FRH	FDL	FDH	LRL	LRH	LDL	LDH
FRL	★							
FRH	★	★						
FDL								
FDH								
LRL		★						
LRH								
LDL								
LDH								

(e) Without the one-third rule &  $\delta_\theta = 8$ 

	FRL	FRH	FDL	FDH	LRL	LRH	LDL	LDH
FRL	★	★						
FRH	★	★			★			
FDL								
FDH								
LRL								
LRH								
LDL								
LDH								

(c) With the one-third rule &  $\delta_\theta = 12$ 

	FRL	FRH	FDL	FDH	LRL	LRH	LDL	LDH
FRL	★	★			★			
FRH	★	★						
FDL								
FDH								
LRL	★	★						
LRH								
LDL								
LDH								

(f) Without the one-third rule &  $\delta_\theta = 12$ 

**Fig. 1.** Statistical Nash equilibriums obtained in each case, where the row player is the manufacturer, and the column player is the retailer.

The average consumers' satisfaction (or the utility) mainly depends on whether the retailer takes the discounted price policy. This policy is favorable to consumers. However, it appears in equilibriums only when the preference is tight ( $\delta_\theta = 7$ ). It may be because consumers buy old milk packages even without a discount in the other cases. It suggests that the linear discounting policy can rarely be economically justified, and other ways of discounting should be tried out.

## 5 Conclusions

To investigate how the one-third rule affects food wastage, we formulated and analyzed a normal-form game played by a manufacturer and a retailer in a milk supply chain. During this study, we also developed a simulation model of the chain and proposed a statistical analysis approach for the game whose payoff matrix needs to be evaluated through simulation. As a result of numerical experiments using the simulator, statistical Nash equilibriums can be identified by the proposed approach. Thus, the approach is expected to be effective also for other complex games defined using a simulator. We further confirmed that, in some conditions, imposing the one-third rule eliminates undesirable equilibriums, including the LIFO policy of the manufacturer, and thus reduces the food waste contrary to ordinary expectations. This provides a possible explanation for the bidirectional effects observed in the social experiments [6]. Since we have conducted experiments only under limited settings, it is necessary to investigate a wider range of conditions. Extending the game model will be the next step. For example, it is an interesting extension to consider the effect of competition among multiple manufacturers and multiple retailers. Verifying the results using human subjects, for example, on a serious game like [12], is also important.

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