Supplementary Material

1 MILK SUPPLY CHAIN

Figure S1 illustrates a general schematic of a milk supply chain and the steps through which milk goes in the chain in the United States. Milk producers (i.e., farmers) store their raw milk in bulk tanks until tanker trucks transport it to a processing facility. At the processing facility, the raw milk is unloaded and stored in silos in which it cannot stay more than 72 hours (Food and Drug Administration, 2017; Lütke Entrup et al., 2005). Then, it goes through the pasteurization process such as HTST pasteurization. HTST pasteurization is a continuous process whereby every particle of milk is held at or above pasteurization temperature (i.e., 72°C (161.6°F)) for a minimum amount of time (i.e., 15 seconds) (Food and Drug Administration, 2017). The pasteurized milk (i.e., processed milk) then is packaged and stored until transported to distribution centers by temperature-controlled trucks. Note that many processors deliver their final products (i.e., packaged HTST pasteurized fluid milk) directly to retail locations where they will be available for the consumers to purchase. The focus of this paper is on the production and processing levels which are shown with the blue rectangles in Figure S1.

2 SPORE REDUCTION TECHNOLOGIES

MF is a separation process that is currently used in different industries (e.g., dairy, food, and beverage) (Synder Filtration, n.d.). An MF unit utilizes a semi-permeable membrane with a greater pore size (range of 0.1 μm to 10 μm) compared to ultrafiltration (range of 0.01 μm to 0.1 μm) or nanofiltration (range of 0.1 nm to 10 nm), to remove spores and bacterial cells (Rysstad and Kolstad, 2006; Synder Filtration, n.d.). It allows most dissolved substances such as minerals and lactose to pass whereas non-dissolved particles such as bacteria and spores will be filtered out, leading to reduced bacteria and spore counts (Tetra Pak, n.d.; SPX FLOW, Inc., n.d.). BF, also called bacterial or centrifugal clarifier, is applied before heat treatment (e.g., HTST pasteurization). Using centrifugal force, it removes spores and bacteria, both living and dead, and separates them from the milk (Market Milk, 2012; Zaheer et al., 2019). Note that both of these units remove the bacterial spores whereas HTST treatments only kill non-spore-forming bacteria and leave spores in the milk (Market Milk, 2012).

According to experts at an SRT company, MF units can filter 10,000-40,000 liters of milk per hour. Their purchasing cost is between $1-2M with a life expectancy of at least 20 years. The major maintenance cost of an MF unit is its membrane filter which requires to be replaced every five years with the cost of $500k. There are limited resources regarding MF electricity usage (e.g., Hurt et al. (2015)). We use expert opinions in calculating the motor rate of MF units. Using the average price of electricity for industrial consumers, 6.85 cents/kWh (U.S. Energy Information Administration, Nov 2019), we calculate the electricity cost of processing one HGP of milk to be between $0.0008-$0.00013. MF can reduce bacterial counts by 99.84-99.99% (Boor and Fromm, 2006; Pafylias et al., 1996; Elwell and Barbano, 2006) which is equal to 2.80-4 log reduction. This value is 99-99.9% (i.e., 2-3 log reduction) for spores (Rysstad and Kolstad, 2006). In our model, we use the reduction of 3 log10 MPN/HGP.

There are different types of BF units with different capacities and electricity usage on the market. Based on the data obtained from TetraPak (2014), the nominal capacities of nine different BF units are between 5,000-40,000 L/hr with a motor rate of 15-42 kW based on which we calculate the electricity cost of processing one HGP of milk is between $0.00014-$0.00039. For each specific instance, the type of BF unit to purchase is based on its annual processed milk volume. Calculating so, we take into account that

double-BF requires double capacity. In addition, according to experts and our industry partners who are currently using BF, a unit cannot be used more than 10-19 hours a day. We used 16 hours as the maximum time a BF unit can work a day when deciding which BF unit should be used for an instance. Purchasing a BF unit can cost between $300,000-$500,000 along with a $100,000 installation cost and its life expectancy is at least 20 years. The maintenance cost is roughly $20,000 a year. According to experts, the spore reduction by single-BF is equal to 1.3 log10 MPN/HGP. This value increases to 2.3 log10 MPN/HGP when double-BF is performed. Note that all the costs associated with MF and BF units are translated to daily cost based on leasing with an industry loan which incurs interest at a rate of 6%.

3 MONTE CARLO MODEL

The model developed by Buehler et al. (2018) uses Monte Carlo simulations to predict the concentration of psychrotolerant spore-formers in an HGP of milk stored at 6°C from day 14 of shelf-life and onwards. Model predictions are based on probability distributions describing parameters for the initial spore concentration in the farm bulk tank raw milk, frequency of different psychrotolerant spore-formers in farm bulk tank raw milk, as well as the growth characteristics of these spore-formers in terms of growth rate, lag time, and carrying capacity at 6°. Each simulation comprises of 100,000 iterations, each represented an HGP. Therefore, the model predicts the concentration of psychrotolerant spore-formers in an HGP of milk for 100,000 different combinations of randomly selected parameter values.

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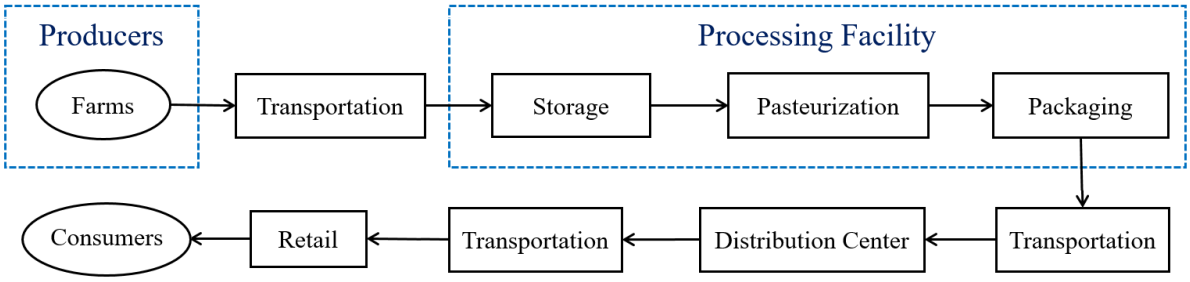

Figure S1. Milk supply chain