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Application of quality cost and quality loss function in food supply chain systems modeling

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Abstract: The food industry is one of the most critical industries for the society. The food supply chains not only fulfill the human daily needs, but also contribute to the economical development of domestic and, in many cases, off-shore economics. In this paper, we propose a basic model for evaluating and optimizing the performance of the retailers in food supply chain systems. The basic model can be extended to different scenarios such as 1) producer with retailer functions, 2) producer with no retailer functions, and 3) retailer with no production functions. Within each model, the performance of different stakeholder (either the retailer or the producer) is evaluated based on the food quality of nutrition value, physical sense quality, and the opportunity cost of food product risks. Specifically, 'Cost of Quality' and 'Quality Loss' have been integrated into our models.

Keywords: Food Supply Chain, Quality Cost Models, Food Quality Loss

1. Introduction

Worldwide, the food industry has recently drawn much attention due to issues related to human health and safety. For any economic entity, whether a country, a province, a city, or a district, the food supply system can be viewed as a complex supply chain. Subjected to geographical boundaries and different regulating policies within the entity, food supply chain deals with suppliers from domestic and international sources. The performance of such a system is heavily based upon the interactive activities between other business entities (or nodes). It follows the similar chain structure as the manufacturing industries but the structure is more complex and the variety of the food products is much more diverse. Today, whether we walk into a modernized grocery store in the West countries or visit a traditional food market in the developing countries, customers can find food items from different origins and from domestic or imported sources, whether these items are fresh, canned, or preserved food. By examining the specific characteristics of the food products, we outline the main factors that distinguish food supply chain from other industry including 1) the food quality and safety that influences the human health, 2) weather related variability, 3) limited usable shelf life, and 4) demand and price variability. All of these factors have increased the complexity of food supply chain issues.

2. Review of Previous Work

In this paper, costs are grouped into two categories, as the tangible and intangible costs. Tangible costs are the cost that can be measured directly, or could be measured according to historical data. Intangible costs are the costs that associate with the potential loss from product storage, usage, and future consequences. Another approach to define tangible cost and intangible cost is: tangible costs are the costs that has identifiable source and could be quantified; and intangible costs are the costs that could be identified, but hard to be quantified. Quantification of intangible costs is conducted based on several existing methods, such as Taguchi's quality loss function.

2.1. Costs of the loss from food product value

The value of food products includes two parts, the nutritional value, and the physical senses value. Traditionally, these two categories of value are considered as one in modeling. Previous models include zero-order reaction kinetics, first-order reaction kinetics, fractional conversion kinetics, the Bigelow model, and non-linear microbiological death model (Martins, 2006). Zero-order reaction kinetics is the traditional model, with simple calculation but with larger errors in estimation. First-order reaction kinetics and fractional conversion kinetics are models based on the experiments by changing the content during certain stages for food storage. The Bigelow model and non-linear microbiological death model are models that have been used to illustrate the changes of nutrients within the food product during a more complex situation, including the effects of changes in temperature during food cooking and after (Manuel et. al., 2009). In most of the literatures, the costs due to the loss of product value is considered as result of food deterioration, and normally is modeled with linear or exponential deterioration rate to illustrate the cost of such loss. Their assumption is that, the reduction of inventory level is a result of joint operation of both demand and deterioration. Two models could be used as being developed by Fujiwara (1993) with linear deterioration rate, and Chung and Huang (2007) with an exponential deterioration rate.

2.2. Food Risk

Quantification of risk is part of the risk assessment process. Due to the difficulty to gather all information regarding the risk, semi-quantitative risk assessment has been used. In this method, value of risk could be represented in forms of linguistic, numerical scales, and quantitative measures of the risk.

Huss (2009) developed a semi-quantitative assessment system to evaluate the risk of seafood products. He created six categories of risk factors, and using symbols of "+", "-" to represent the risk for each factor. By calculating the overall number of "+" to rank the all risks associated with seafood product. Other approaches use scale of individual category of risk factors to calculate the overall risk. Van Gerwen et.al (2000) developed a SIEFE system, and by setting different scale of risk factors on each risk level, the overall quantitative risk could be obtained.

Ross and Summers (2002) developed another model with nine risk input values, by completing the six steps calculation; the overall risk could be obtained. The most important part of their model is the concept of comparative risk. This risk contains the evaluation of probability of illness over all servings, annual exposures per person in a daily basis, and the hazard severity factor (Figure 1).

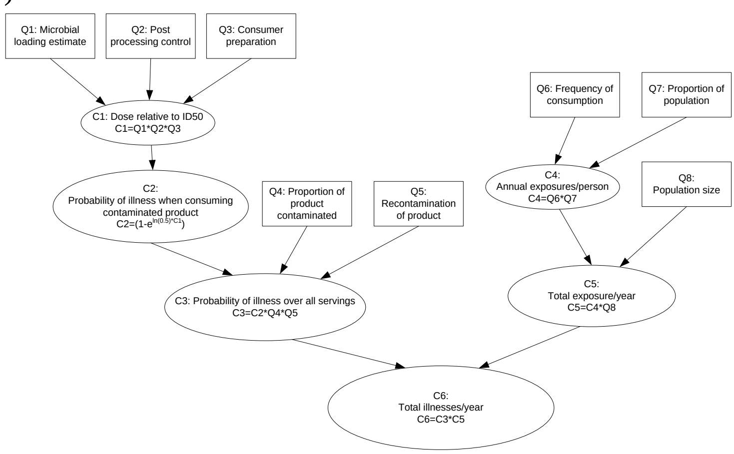

Fig.1: Chain of Factors in Ross and Sumner's Food Risk Model (2002).

Liu et. al. (2011) conducted a literature review recently on the task of vendor selection within supply chains based on the criteria of risk management. Auyong et. al. (2011) also reviewed relevant literatures about safety and health management in logistics and supply chains.

3. Design and Methodology

In this research, our objective is to evaluate and optimize the food product quality in food supply chains. Criteria used in our models include the cost and risk factors, that are further divided into tangible and intangible categories. To facilitate the modeling of the food supply chains, we made the following assumptions:

1. Replenishment rate is infinite and lead time is zero. And shortage is not allowed.
2. The food products follow the general form of deterioration.
3. All cost parameters are known in advance.
4. Cost and retailing price for the food products at the retailers are known and fixed.
5. Demand for a food item is assumed to be deterministic. No seasonal effect.
6. Deterioration process is assumed to start when retailer receive product, and no deterioration during transportation.
7. During storage, transportation, and on shelf period, the environment, such as temperature, lighting, packaging quality, are assumed to be steady and unchanged

Notation:

D, d Annual(D) and daily demand(d) for a food product at the retailer, $d=D/365$.

Q Order quantity, $Q=d*n$, where n is days for each ordering period.

C_o Ordering cost, all cost associated with the placement of an order.

C_s Setup cost, all cost associated with the setup of product for each batch

Q_p Size for each production batch.

S_r Retail price for food product at the retailer.

S_p Price for food product at the producer.

y Producer's quality level (in Taguchi Quality Loss function concept).

H Holding cost rate at the retailer, during the storage and on shelf period before being purchased by consumers.

Q_{10} Food deterioration parameter, which is used in the model for loss of nutrition.

F_1 Food product life labelled, which is based on the storage temperature of T_1.

F_2 Food product real shelf life, which is based on the storage temperature of T_2.

k Food product deterioration rate or quality loss rate.
k_1: Deterioration rate from micro-organisms' activities.
k_2: Deterioration rate from enzymes' activities.
k_{NL} Food product nutrition quality loss.
k_{PS} Food product physical senses quality loss.
L_{NL} Nutrition loss.
L_{PS} Physical senses loss.
P_p Production cost per unit of food product.
P_q Cost of quality per unit, a sum of internal failure cost, prevention cost and appraisal cost.
P_t Cost of transportation per unit.
α Percentage of cost for the producer.
β Percentage of cost for the retailer.
λ Percentage of cost for the customer, where $\alpha + \beta + \lambda = 1$
Q_i Probability of occurrence for a certain risk related activity i.
a Weight assigned to the nutrition loss for food items.
b Weight assigned to the physical senses loss, where $a+b=1$.

3.1. Direct Cost, Cost of Quality, and Food Quality Loss

Direct cost, are the cost associated with the production of food product, management, storage, transportation, and other costs. Costs under this category are:

1. Cost of production: includes cost for the purchasing and usage of raw material, direct labour cost associated with production of product;
2. Set up cost for production: cost for the setup for each batch of production, potential failure in quality results in defect of product in whole batch;
3. Cost of transportation: cost of transport products from manufacturer to retailer;
4. Ordering cost: cost for retailer to make order for replenishment; and
5. Holding cost: cost for retailer to store products before sales. This cost includes the cost occurs in storage, and on shelf.

Cost of quality, are these cost that are relate to the tasks of quality issues and quality improvement. In this paper, we adopt the common cost of quality categories, i.e., internal failure cost, external failure cost, appraisal cost, and prevention costs. Due to the unique characteristics of food products and food industry, external failure costs are discussed and modeled separately from the other costs. External failure costs are used to represent the cost related to the quality loss of food that could influence the action of customer. These could be measured as the level of satisfaction of product.

According to research literature in food science as discussed in the review section, quality factors for food could be divided into two major categories: 1) nutrition & energy supply, and 2) quality related to physical senses. Nutrition and energy supply serves the basic function of food: to supply energy and bio-chemical needs to maintain the survival and functions of human body. Quality senses includes the physical senses customer received from the food product. Such senses include sight, touch, smell, taste, and even hearing. In general, these senses are grouped into appearance factors, textural factors, and flavor. As there are existing rigid governmental regulations in terms of food safety and shelf life, the issue of nutrition loss for food items is usually dominated by the other concern of customers - the deterioration of food in terms of physical senses. Generally, customers can easily detect food items that have been on shelf longer based on the physical senses, but less likely to be aware of the possible nutrition loss of food items.

3.1.1. Nutrition and Energy Supply Loss

To quantify the food nutrition loss over the time factor, a widely used method of Q_{10} in food science is adopted in our model. The equation of Q_{10} is used to describe the duration of storage to reach the same nutrition level under different temperature.

$$f_2 = f_1 * Q_{10}^{\frac{\Delta}{10}} \tag{1}$$

In equation (1), f_1 is the reference duration at reference temperature T_1, f_2 is the duration of the targeting temperature T_2. Δ is the difference between targeting temperature T_2 and sample temperature of T_1. If we consider F_1 to be the labeled shelf-life of food product, which has a higher temperature than normal storage temperature; and F_2 to be the actual shelf-life under the normal storage temperature, we can define the nutrition loss at day F_1 as following. Notice that this 'potential' nutrition loss for the customers is in proportion to the food retail price and the ratio of actual shelf period over the labeled shelf life. For example, a food item has been labeled for a shelf life of F_2 days, when this item has been purchased before on F_1 ($F_1<F_2$), a certain portion (F_1/F_2) of nutrition loss can be expressed as NL_{F1}.

$$NL_{F_1} = a \bullet \frac{S_r}{F_2} \bullet F_1 \tag{2}$$

3.1.2. Physical Senses Loss.

According to food science, there are 1) appearance factors, 2) textural factors, and 3) the flavor factors, that are considered physical senses by consumers on food products. Appearance factors usually include size, shape, wholeness, color, consistency for liquid, and so on. Textural factors include hand feel and mouth feel of firmness, softness, juiciness, chewiness, grittiness. Flavor factors include both taste and odor. The loss of physical senses for food products is normally the result of food deterioration. Major causes for food deterioration include:

1. Growth and activities of microorganisms, such as bacteria, yeast and so on;
2. Activities of natural food enzymes;
3. Insects, parasites, and rodents;
4. Temperature; moisture and dryness; air (particularly oxygen); and light;
5. Time duration.

3.1.2.1. Growth and activities of microorganisms

According to food science, if the original number of microorganisms in food product is A, then the number of microorganisms in food after time *t* will be:

$$N = A \bullet t^2 \quad (3)$$

And the quality loss can be formulated as in proportional to the number of microorganisms in the food. The more microorganisms, the more quality loss the customer is suffering. If the loss rate is *k*, then the loss from microorganisms can be:

$$L_{micro} = k \bullet N = k \bullet A \bullet t^2 = k_1 \bullet t^2 \quad (4)$$

3.1.2.2. Activities of natural food enzymes

According to Potter (1986), bacteria or microorganisms are the greatest factors in food deterioration, and the activity of enzyme is the second greatest. However, certain factors that impact the activity of microorganisms, such as temperature, moisture level, light, radiation and so on are also applicable to enzymes. We therefore define the food quality loss due to enzymes as the following:

$$L_{enzyme} = k_2 \bullet t^2 \quad (5)$$

3.1.2.3. Insects, parasites, and rodents

With proper packing and storage of food items in modern food retailer facilities, the impact of insect, parasites, and rodents will not be considered in our model.

However, when dealing with the storage of raw material (e.g. national strategic reserve of grains), this factor should be considered as the impact will be significant

3.1.2.4. Temperature, moisture, dryness, air, oxygen, and light

Based on the research by food scientists, storage temperature, moisture, air or oxygen levels, and light all can affects the food quality loss. However, the impact is already reflected previously in microorganisms and enzymes. Hence, not consider here.

3.1.2.5. Time

It is clear that one of the most important factors for food quality loss calculation due to food storage and food shelf life is dominated by the time factor. However, the impact of time factor has been incorporated into other categories such as the microorganism and enzymes growth.

In summary, we can calculate the overall deterioration rate for physical senses loss as:

$$k_{PS} = k_1 + k_2$$

And the quality loss due to physical senses for one product unit can be expressed as:

$$L_{PS} = L_{micro} + L_{enzyme} = k_1 \bullet t^2 + k_2 \bullet t^2 = k_{PS} \bullet t^2 \quad (6)$$

3.2. Quality Loss Functions and Food Quality Loss due to Physical Senses

Taguchi's quality loss function is originally designed to evaluate the quality loss associated with the design of tolerance in manufacturing industry. There are four different quality loss functions:

- *Nominal Value the Best - symmetrical tolerance interval (N-Type-Symmetrical)*
- *Nominal Value the Best - asymmetrical interval (N-Type-Asymmetrical)*
- *Larger Value the Better - (L-Type)*
- *Smaller Value the Better – (S-Type)*

In our case, the longer a product has been stored, the greater the loss customer will be suffering. Whether we are using the time factor, the number of microorganisms, or the amount of enzymes, it is apparent that *Small-Value-The-Better (S-Type*) quality loss function is appropriate in this case. The general Small-Value-the-Better quality loss equation defined by Taguchi is expressed as:

$$Quality - Loss(S - Type) = \frac{A}{\Delta^2}\sum(diviation^2)$$

Equation (6) can be modified according to the Taguchi format as following within which A is replaced by the price of a food product S_r and Δ is the labeled shelf life F_1.

$$L_{PS} = k_{PS} \bullet t^2 = \frac{S_r}{F_1^2} \bullet t^2 \quad (7)$$

As indicated, the quality loss for one unit of a food product for a specific shelf period of t is given by equation (7). Within a supply chain, the retailer may place Q units of food products for each order and $Q=d*n$ where d is the daily demand and n is the length of each ordering period. Within each ordering period, food items may be stored on shelf from 0 to n days, waiting to be purchased by the customers. We can therefore derive th**e Total Quality Loss due to physical senses as:**

$$L_{PS} = \int_0^n (d) \bullet (k_{PS} \bullet t^2) dt = \frac{d \bullet k_{PS} \bullet n^3}{3} = \frac{d \bullet S_r \bullet Q^3}{3F_1^2 d^3} = \frac{S_r \bullet Q^3}{3F_1^2 d^2} \quad (8)$$

3.3. Food Risks Associated with Time

In the work by Ross and Summers (2002), they assume the food risk to be a compound number by multiplying Q_1 through Q_8, that deal with risks from microorganisms, processing, preparation, contamination and additives, as well as frequency of consumption and market share over the entire population over a year.

$$Food\text{-}Risk\text{-}Over\text{-}Time = \prod_1^8 Q_i$$

One of the main drawbacks is the assumption of the constant risk levels for food items, regardless of the time spent on the shelf. In our model, we combine all the risk factors in Ross and Summers model and eliminate the frequency of consumption, market share, as well as population and exposure distribution. We assume the food risk for a product ordering cycle is given by

$$R = k_{fr} t^2 \quad (9)$$

Where k_{fr} is the coefficient of financial risk, and t is the time. The overall risk for a certain period of t is given by

$$\overline{R} = \int k_{fr} t^2 dt = \frac{1}{3} k_{fr} n^3 = \frac{1}{3} k_{fr} \frac{Q^3}{d^3} \quad (10)$$

As the quantification of risk over time should consider the time period of product shelf life, so in the equation above, t value can be given by the product shelf life F_1, and the coefficient of k_{fr} should be obtained according to different food types. One possible source for the k_{fr} value can be obtained by adopting Ross and Summers model (2002) within which:

$$k_{fr} = \frac{Q_1 \times Q_2 \times Q_3 \times Q_4 \times Q_5 \times Q_6 \times Q_7 \times Q_8 \times \eta \times HS \times (Penalty - Cost)}{F_1^2} \quad (11)$$

Where Q_1 through Q_8 used by Ross and Summers were defined earlier in the review section and η is the market share and HS is the hazard severity factor (value in the range of (0.0, 1.0) with 0.0 for low health hazard and 1.0 for fatal health issue). Penalty cost is usually estimated for litigation punitive damage, North American statistics indicated that the value for Penalty Cost for food related cases was on average in the range of millions of dollars.

3.4. Objective Function for the Food Supply Chain Model

In the food industry, there are typically three business models. The more traditional model is the case that food producer is also the distributor. The other two cases are the producer or retailer simply focuses on their core function in the supply chain system, which is: producer only performs the function and activities of producer, and retailer only operates the core functions and activities of retailer. The last case is very similar to the traditional EOQ model.

In this paper, we will present only the Total Cost calculation for the first business case, i.e., the food producer is also distributing its food products to the consumers through its retailing channel.

The Total Cost including all direct costs(production, transportation, shortage, inventory holding, etc.), quality loss cost(nutrition loss and physical sense loss), as well as cost associated with food risk factors is summarized as:

Total Cost =	$P_p \cdot D$	production cost
+	$C_s \cdot \frac{Q}{y \cdot Q_P}$	setup cost
+	$P_q \cdot D \cdot \frac{(1-y)}{y}$	yield and defective cost
+	$P_t \cdot D$	transportation cost
+	$C_o \frac{D}{Q}$	ordering cost
+	$h \cdot S_p \cdot \frac{Q}{2}$	inventory holding cost
+	$\frac{a \cdot S_r \cdot D \cdot Q}{2F_2 \cdot d}$	nutrition loss cost

+ $\frac{b \bullet Sr \bullet D}{3F_1^2 \bullet d^2} \bullet Q^2$ physical senses loss cost

+ $\frac{k_{fr}Q^3}{3d^3}$ food risk loss (converted cost) (12)

Similar to the traditional EOQ model, optimization technique is then applied to find the optimal ordering quantity that minimizes the Total Cost. Due to the limit of paper length, we will not present the solution procedure here.

4. Conclusion

In this paper, we present a model for food supply chain procurement decision making by considering the traditional EOQ factors as well as additional factors such as food nutrition loss, physical senses quality loss, and food risk financial loss. Preliminary results on four different food items, not presented in the paper, demonstrated that the feasibility of adding the additional factors in a food supply chain decision making process. Our future work will be to refine the food risk financial loss factor and to expand the model for different scenarios such as including distributors, and producers.

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