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The Green Supply Chain Design and Marketing Strategy for Perishable Food Based on Temperature Control

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Abstract: With the intensification of global warming and the levy of energy tax, more industries are paying attention to energy saving and reduction of carbon footprint. For the food industry, energy cost in the supply chain of perishable food is quite high because of cold-chain transport and storage. Therefore, the efficacies of cold chain management and inventory control are the key factors that increase the efficiency of food supply chain and make it more ecological. This research analyzes the degradation process of perishable food and determines the optimal temperature of the cold chain as well as the optimal price to maximize the channel profit. We prove that there is an optimal price with a certain temperature and develop an efficient search algorithm to find the optimal temperature. We also perform sensitivity analyses to test which parameters affect the channel profit significantly. Numerical experiments are conducted to illustrate the proposed models.

Keywords: supply chain model; marketing strategy; perishable food; temperature control

1. Introduction

Perishable food's short lifetime, spoilage, and demand uncertainty cause the difficulty of managing perishable food supply chains [1,2]. Moreover, the necessity of cold-chain transport and storage for perishable food leads to high energy costs. The spoilage rate of food reaches as high as 15% in most of European retail stores [3–5]. This results in the annual economic losses of up to several billion Euros. It is of importance to design green supply chains with a marketing strategy to reduce energy costs and increase the total profit. In general, the quality of perishable food decays at a certain rate and the rate is affected by many factors, such as the characteristics of food, storage temperature, and atmospheric environment. Among them, the environment temperature is a main controllable factor of the supply chain and an important factor influencing food safety during the whole procedure of food processing, transportation, storage, and sales [6]. Retailers in different scales often adopt completely different quality control methods and marketing strategies. For example, some small seafood vendors usually choose a single or a few varieties of seafood to sell at room temperature or lower temperature by using ice and other simple cooling methods. Meanwhile, those vendors often set a relatively low price to promote the market, which could consequently reduce the transportation cost and sales cost. By contrast, supermarkets could cut down the unit purchasing cost through buying a large quantity of items. However, many varieties of products, as well as the long sales cycle time, force managers to adopt marketing strategies including the entire cold-chain transportation and preserving the food in a refrigerated cabinet at the selling stage [7]. To keep the freshness of food products, massive energy is consumed during the process of cooling phases and cold-chain transportation, which consequently aggravates environmental pollution and increases the carbon footprint. Furthermore, since energy prices rise continuously, the total cost of food supply chain is getting higher so as to enlarge the price differences of perishable food between the places of origin and the destination markets, which may suppress the customers' demand. It is necessary to apply marketing strategies (such as pricing discounts and temperature control) and design a green supply chain for perishable food to reduce the total cost and energy consumption. Some studies have developed approaches to model characteristics of perishable food items and marketing strategies in the food supply chain [8–14]. However, the existing research rarely provides useful theories or proof demonstrating how the marketing strategies are affected by both the energy consumption and quality change of perishable food in storage. Hence, on the basis of the quality control of perishable food, this paper comprehensively studies the cost and energy consumption of perishable food in the process of production, transportation, and sales, and then develops integrated marketing strategies with respect to the pricing, temperature, and quality control.

Green supply chain management has been started early in the field of theoretical research. With global warming and environmental deterioration, green supply chain management has become an important strategy for the sustainable development of various industries from the perspective of enterprise practice. In general, the green supply chain has an effect on decision-making of companies in two aspects. First, green concepts can attract consumers and motivate their purchasing intentions. Liu et al. [15] established a two-level green supply chain model where the demand is directly influenced by consumers' green preference, and conducted research on the impact of the number of peer competitors in the supply chain on each competitor's decision-making. Swami and Shah [16] developed a green cooperative supply chain consisting of a single retailer and a single supplier, which can improve the green level of products and the profit of the supply chain by comparing it with a non-cooperative supply chain. Second, the increase in energy prices and the government's tax policy force enterprises to reduce energy consumption, and eventually realize total cost reduction. Zanoni and Zavanella [12] proposed the food supply chain management problem with consideration of both specific temperature control and the effects of the size of packaging on the cost of supply chain. Recently, RFID technology is well applied in companies for the design of an agile food supply chain and hence enhances the effective management of perishable food products [17–19]. Hong et al. [20] analyzed the role of radio frequency identification (RFID) technology in food supply chain by taking a convenience store in Taiwan as an example. They pointed out that RFID technology can reduce both management cost and energy consumption.

Another major factor affecting food sales is the food price. Many consumers are very sensitive to food prices. Due to the perishable nature of food, many retailers reduce the economic loss caused by the spoiled food by adopting some marketing strategies such as quantity discount and "buy one get one free". Therefore, pricing for perishable food is directly related to the profits of the whole food supply chain. Wang and Li [14] developed a pricing model for perishable food based on dynamic food quality evaluation, and gave an optimal strategy for single and multiple price reductions in their proposed model. The price will affect food sales and thus have an impact on inventory strategy. Wee [11] proposed a joint decision strategy for pricing and inventory in the context of decreasing demand.

In previous studies, few researchers paid attention to the impact of temperature control on the profit of supply chain during the process of production, processing, and sales for perishable food. Temperature control can have an impact on the spoilage rate of perishable food and influence the sales strategy. Keeping the temperature at a lower level can reduce the loss caused by food deterioration at the expense of consuming more energy. While a relatively higher temperature can reduce energy consumption but speed up food deterioration. Hence, this paper proposes the management strategies suitable for food supply chain by comprehensively considering temperature control during the process of food processing and food transportation, and sales and inventory management in the retail stage, aiming to achieve the purpose of improving the total profits of the perishable food supply chain.

2. Model Formulation for Green Supply Chain with Perishable Food

In this section, we propose a mathematical model for the channel profit of the whole supply chain including food cooling costs, transportation costs, sales revenue, and inventory management costs in retail.

2.1. Food Quality Deterioration Model

Quality deterioration for perishable food is a very complicated process. It was quite difficult to predict how the quality of perishable food changed before modern tracking, wireless communication, and chemical detection technology were developed. With the development of modern technology, such as RFID and the humidity-temperature sensor chip, it has become possible to monitor food quality. Labuza [21] and Peleg et al. [22] proposed models to predict the quality change of perishable food. Based on the existing models for quality change, Blackburn and Scudder [23], Wang and Li et al. [14] tried to develop a supply chain model for perishable food by taking the remaining shelf life or remaining nutrition of food as indicators of food quality.

According to Labuza [21], the degradation of food quality is affected by the following factors: the storage time, storage temperature, and condition of ambient atmosphere. The degradation of food quality is expressed as

$$\frac{dq}{dt} = -kq^n \tag{1}$$

where q indicates the food quality, t stands for the time period in storage, k is the degradation rate of food, n is the index of chemical reaction. In this equation, n can be equal to 0 or 1, depending on the course of the food degradation. When n = 0, the food quality decays at a constant rate; when n = 1, the quality decays exponentially. Since most food degrades exponentially in real life situations, we take n = 1 in this paper. In Equation (1), k can be expressed as

$$k = k_0 e^{-(E_a/RT)} \tag{2}$$

where k_0 is a constant rate; E_a is the activation energy, which is an empirical parameter reflecting the temperature; R is the gas constant; T is the thermodynamic temperature. According to Equations (1) and (2), the quality of perishable food at time t can be described as

$$q(t) = q_0 e^{-k_0 t e^{-(E_a/RT_0)}} \tag{3}$$

In the process of transportation and sales, we generally assume that the storage temperature is a constant for the convenience of calculation. Based on this assumption, Peleg [22] put forward Weibull-power law model to describe the quality degradation of perishable food in the isothermal state. Two variables were used in the model: storage time and storage temperature. The model is introduced as

$$q(t,T) = q_0 e^{-g(T)t} \tag{4}$$

where $g(T)$ is a function with respect to the temperature. In the research of Peleg [22], $g(T)$ is expressed as the following empirical model

$$g(T) = \ln(1 + e^{m(T-T_c)}) \tag{5}$$

where T is the storage temperature; m is the deterioration rate parameter with respect to temperature; and T_c is constant number.

2.2. Demand Model

In the retail stores or supermarkets, demand for perishable food is affected by various factors, such as the scale of market, product quality, price, and discount. In this research, we assume the demand rate of perishable food mainly depends on two factors: product quality and price. The demand rate at time t is expressed as

$$D(t) = a - bp + cq(t, T) \tag{6}$$

where a stands for the market scale, b is the price elasticity, c is the consumer's sensitivity to product quality, p is the selling price, $q(t,T)$ represents the product quality.

We set the replenishment cycle time to be a constant t_1 and transportation time be t_0, due to the high unit transportation cost and stable expiration date of perishable food. Thus, food quality when the food is delivered to retailers can be described as

$$q_1 = q(t_1, T) = q_0 e^{-g(T)t_0} \tag{7}$$

The demand function when the food product arrives at retail stores at time t is expressed as

$$\begin{aligned} D(t) &= a - bp + cq_1 e^{-g(T)t} \\ &= a - bp + cq_1 e^{-\ln(1+e^{m(T-T_c)})t} \end{aligned} \tag{8}$$

2.3. Coefficient of Performance for Refrigeration

At every stage of the supply chain, the temperature affects the energy consumption and cost of the supply chain, especially when perishable food starts its cooling process after being produced. Rong et al. [13] proposed the so-called coefficient of performance (COP) for refrigeration, which is shown as

$$COP = \frac{E_{cold}}{E_{hot} - E_{cold}} = \frac{T_{cold}}{T_{hot} - T_{cold}} \tag{9}$$

where E_{hot} is the heat that products being refrigerated need to send out during the refrigeration process, E_{cold} is the heat that refrigeration equipment needs to absorb. T_{hot} and T_{cold} are higher and lower thermodynamic temperatures, respectively. We usually set T_{hot} as the room temperature (20 °C) and T_{cold} as the target cooling temperature. For example, with T_{hot} = 293 K (20 °C) and T_{cold} = 243 K (−30 °C), $COP_{-30°C}$ = 4.86; with T_{hot} = 293 K (20 °C) and T_{cold} = 258 K (−15 °C), $COP_{-15°C}$ = 7.37. We can caculate the energy consumption for different targeting temperatures. Asume energy consumption at −30 °C is 1, the same item is cooled from room temperature (20 °C) to −30 °C and −15 °C, respectively. We can see that the energy consumed from 20 °C to −15 °C accounts for 65.9% ($COP_{-30°C}/COP_{-15°C}$ = 0.659) of that from 20 °C to −30 °C.

2.4. Model for Perishable Food Supply Chain

In this section, we develop a mathematical model for perishable food supply chain associated with the procedure of processing, cooling, and transportation to sales. In the supply chain model, the profits of the supply chain are composed of the following elements: sales revenue, production (or purchasing) cost, energy cost consumed in the cooling process, transportation cost, and inventory cost in the sales process.

First, t_1 is the sales time (i.e., length of the replenishment cycle); sales revenue is equal to the price multiplied by the demand according to the demand model given above. Therefore, the sales revenue is expressed by

$$p\int_0^{t_1} D(t)dt = p(a-bp)t_1 + pcq_1(1-e^{-g(T)t})/g(T) \tag{10}$$

Second, let C_0 and Q denote the unit production (or purchasing) cost and the replenishment quantity, respectively. Since the demand is given in advance, the replenishment quantity each time is equal to the demand. Then, the production (or purchasing) cost can be described as

$$C_0Q = C_0\int_0^{t_1} D(t)dt = C_0(a-bp)t_1 + C_0q_1c(1-e^{-g(T)t})/g(T) \tag{11}$$

Third, A_s indicates the fixed cost of cooling process at one time, E_s is the energy consumption needed for cooling the unit item from room temperature (i.e., 20 °C) to the specified temperature (here it is set to be −30 °C science that most refrigerated transportation temperature or the storage temperature is not lower than −30 °C), C_e is the unit energy price, T_s is the targeted cooling temperature, ρ_{Ts} is the energy consumption ratio of cooling the product to the targeted temperature and the specified temperature (−30 °C). Thus, we calculate the processing and cooling cost for one replenishment cycle by

$$A_s + E_sC_e\rho_{T_p}Q = A_s + E_sC_e\rho_{T_p}(a-bp)t_1 + E_sC_e\rho_{T_p}q_1c(1-e^{-g(T)t})/g(T) \tag{12}$$

Fourth, let A_c be the fixed cost of the transportation at one time, T_c be the transportation temperature, E_c be the energy consumption needed by each transportation in the specified temperature (−30 °C), C_e is the unit energy price, ρ_{Tc} is the energy consumption ratio of the transportation temperature and the specified temperature. Then, the transportation cost at one time is

$$A_c + E_cC_e\rho_{T_c} \tag{13}$$

Finally, let I_t denote the inventory level at time t and I_t can be expressed by the difference between the replenishment quantity and the accumulated demand before time t

$$I(t) = Q - \int_0^{t} D(t)dt \tag{14}$$

Let h denote the inventory cost per unit per unit time, T_h denote the storage temperature in the sales process, E_h denote the energy consumption needed for maintaining the unit commodity at the specified temperature (−30 °C) per unit time in the sales process, C_e is the unit energy price, ρ_{Th} is the energy consumption ratio of maintaining the product at the storage temperature and the specified temperature in the sales process,

$$(h + E_hC_e\rho_{T_h})\int_0^{t_1} I(t)dt = (h + E_hC_e\rho_{T_h})[Qt_1 - \frac{1}{2}(a-bp)t_1^2 + \frac{cq_1t_1}{g(T)} + \frac{1-e^{-g(T)t_1}}{g(T)}] \tag{15}$$

In conclusion, the total profit of the supply chain is

$$\pi = p\int_0^{t_1} D(t)dt - C_0Q - (A_s + E_sC_e\rho_{T_p}Q) - (A_c + E_cC_e\rho_{T_c}) - (h + E_hC_e\rho_{T_h})\int_0^{t_1} I(t)dt \tag{16}$$

For convenience, we assume that T_s (the targeted cooling temperature) = T_c (the transportation temperature) = T_h (the storage temperature during the sales process) = T.

Thus, the total profit of the supply chain becomes

$$
\begin{aligned}
\pi(p,T) \quad = \quad & p\int_0^{t_1} D(t)dt - C_0Q - (A_s + E_sC_e\rho_T Q) - (A_c + E_cC_e\rho_T) \\
& -(h + E_hC_e\rho_T)\int_0^{t_1} I(t)dt \\
= \quad & p(a-bp)t_1 + pcq_1(1-e^{-g(T)t})/g(T) - C_0(a-bp)t_1 \\
& -C_0q_1c(1-e^{-g(T)t})/g(T) - A_s - E_cC_e\rho_T(a-bp)t_1 \\
& -E_cC_e\rho_T q_1c(1-e^{-g(T)t})/g(T) - A_c - E_cC_e\rho_T \\
& -(h+E_hC_e\rho_T)[(a-bp)t_1^2 + t_1cq_1(1-e^{-g(T)t})/g(T) \\
& -\tfrac{1}{2}(a-bp)t_1^2 + \tfrac{cq_1t_1}{g(T)} + \tfrac{1-e^{-g(T)t_1}}{g(T)}]
\end{aligned} \tag{17}
$$

In the profit function, the price p and the temperature T are decision variables, while other parameters are assumed to be constant.

3. Optimal Solution and Search Algorithm

In the total profit function, we assume that T has been given and take the second derivative of the price p, then

$$\frac{\partial^2\pi}{\partial p^2} = -2bt_1 < 0 \tag{18}$$

with a given T, we can get the optimal price p by solving the equation $\partial\pi/\partial p = 0$, which is

$$
\begin{aligned}
p = \quad & \tfrac{1}{2bt_1}[at_1 + cq_1(1-e^{-g(T)t})/g(T) + bC_0t_1 \\
& +bt_1E_cC_e\rho_T + \tfrac{1}{2}bt_1^2(h+E_hC_e\rho_T)]
\end{aligned} \tag{19}
$$

Due to the limitations of refrigeration equipment and energy consumption, the minimum temperature of food freezing is usually not less than −30 °C. Perishable food does not need refrigeration when the storage temperature is higher than room temperature. Thus, it is reasonable to set the upper and lower bounds of refrigeration temperature as −30 °C and 20 °C (thermodynamics 243 K and 293 K). We develop a simple algorithm (Algorithm 1) to find the optimal solution.

Algorithm 1. Solution Methodology for Perishable Food Supply Chain

Step 1: Input values of all parameters. Set the refrigerating temperature T = 243 and the optimal solution $\pi^* = p^* = T^* = 0$.
Step 2: Calculate the value of p through Equation (19). Take the values of p and T into π. If $\pi > \pi^*$, set $\pi^* = \pi$, $p^* = p$, $T^* = T$.
Step 3: Let $T = T + 1$, if $T \leq 293$, return to step 2; otherwise, the optimal solution π^*, p^* and T^* are found.

4. Numerical Experiments

In this section, we adopt the values of parameters provided by Zanoni and Zavanella [12], Rong [13], and Wang and Li et al. [14] as shown in Table 1. Table 2 gives the optimal solutions with different values of parameters. The experimental results show that customers' sensitivity to price has a greater impact on the profit of the supply chain. This is also true in practice. The food market usually has a large number of competitors, where consumers have many alternatives to choose and they are very sensitive to food price. Therefore, the accurate measurement of customers' sensitivity to price in supply chain management and reasonable pricing are of great importance. When the customers are sensitive to price increase, the retailers should cut down the food price to stimulate the market and reduce the loss caused by food deterioration by lowering the storage temperature. Moreover, since the temperature difference ($T - T_c$) is negative, the spoilage rate of the food will increase with the decrease of the value of m. Hence, for perishable food with the higher rate of spoilage, the storage temperature should be reduced and the price be cut down to increase sales.

Table 1. Values of input parameters

Parameter	Value	Parameter	Value
a	60	q_0	1
h	0.001	t_0	10
c	4	t_1	240
C_0	8	E_h	0.001
A_s	50	E_s	0.3
C_e	1.5	A_c	15
E_c	700		

Table 2. The optimal solutions with different values of parameters

m	b	p	T	π
0.22	4	12.308	242	10,224.99
	4.5	11.389	244	5835.08
	5	10.613	247	2826.70
0.23	4	12.305	244	10,320.08
	4.5	11.388	245	5915.70
	5	10.620	248	2890.38
0.24	4	12.302	244	10,408.25
	4.5	11.387	246	5990.68
	5	10.625	248	2950.23

5. Conclusions

This paper considers the pricing and temperature control in the supply chain for perishable food. Through the established supply chain model, we can obtain the optimal pricing and storage temperature of the supply chain. This paper also considers the cost of energy consumption during the process of cooling, transportation, and sales, and analyzes the effects of energy consumption on pricing and replenishment strategies for perishable food. The computational experiments show that when the spoilage rate of food is high, the price should be cut down to stimulate the market and the storage temperature should be decreased to reduce the loss caused by food deterioration. This paper solves the existing extensive management problems in supermarkets, and provides detailed and targeted management strategies for perishable food, which improves the resource utilization and reduces energy consumption. The experimental results also provide meaningful reference for food supply chain management in practice.

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