Dynamic Pricing and Ordering Decision for the Perishable Food of the Supermarket Using RFID Technology

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〈Abstract〉

Product quality of perishable food is significantly affected by the environment. Technological approaches for tracking and tracing such products have attracted increasing attentions in both research and practice. This paper studies how supermarket can maximize profits of selling perishable food through price adjustment based on real-ime product quality and values. This can be achieved by tracing the value of the perishable food based on an automatic product identification technology Radio Frequency Identification (RFID). With the support of the RFID, an optimization model can be developed to enable product tracking and tracing. The analysis of the model shows promising benefits of applying a dynamic pricing policy and obtains the optimal ordering decision in the respect of deterministic demand function.

Introduction

In recent years, supermarkets display more and more perishable food on shelf to draw consumers into the stores (Hennessy 1998). As noted by Glen Terbeek, managing partner of Anderson Consulting, 'In today's world, branded grocery items are the same everywhere; Coke is Coke and Tide is Tide,… but perishables and their presentation are unique'. Perishable products are difficult to manage because of their random weights and their limited shelf lives under different conditions. Coupled with the effect of expiration date and perceived risk on purchasing behavior (Tsiros and Heilman 2005), perishables make it hard for retailers to implement any category management strategies (Litwak 1997).

With the development of technology, real time tracking and tracing product information through Internet based networks appeared. In recent years, an IT based product identification technology, radio frequency identification (RFID), has attracted increasing attentions in supply chain management. Unlike barcode systems, the technology can identify remote products as compared to visual alignment of each product with a scanner. A RFID system can

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communicate with products and update the data on RFID tags simultaneously. Therefore, the technology provides opportunities in the automation of the data capture, product item visibility, and particularly the business process transparency and integration, which will greatly improve the management of perishable food.

A typical example of the successful application of the RFID is Wal-Mart. In 2003, in line with its' corporate mission of continual improvement and cost reduction through the intelligent use of technology, Wal-Mart forced its top 100 suppliers to implement and deploy RFID tagging at the case & pallet level by January of 2005. Wal-Mart's adoption of the technology has proved largely successful, with improved delivery time, reduced re-order lag-time, declined product depletion, as well as reduction of shrink and greater marketing insight into customers' buying habits.

The existing research on RFID or RFID-enabled business models has been focusing on the conceptualization and descriptive analyses on its potential benefits of replacing barcode systems. Quantitative analysis on innovative business models based on RFID data has been rare. In this paper, we first consider a RFID-based methodology for ordering decision and the dynamic pricing schedule of perishable food under a deterministic demand function. We study a supermarket scenario with which the customer demand is price-and -value dependant. Assuming that RFID systems are already in operation in the supermarket, the product value can be assessed by the RFID systems according to automatically captured product properties and related censoring data such as temperature and humidity. The objective is to decide the pricing and inventory policies for the supermarket that orders, stocks and sells a perishable food using RFID systems. Below we first review literature on the dynamic pricing and RFID applications in section two. We then propose our model and show the potential benefits of using RFID technology in section three. Concluding remarks follow in section four.

Ⅱ. Literature review

Dynamic pricing is defined the assignment of different prices to the product items of the same category, considering the individual product characteristics or the changes of the product status. The research in the perishable food pricing has been targeting at maximizing profits (Bhattacharjee and Ramesh, 2000) and optimizing operations performance in the stock control (Blackburn and Scudder, 2003). Bhattacharjee and Ramesh (2000) developed a profitmaximization pricing model in which a single product has a fixed perishing life and the deterioration of the product was considered for a time period over which total demands are allocated through managing the price - dependent demand. Blackburn and Scudder (2003) developed an optimal ordering model which considers the loss of perishable product values at different supply chain stages. They focused on value deterioration characteristics of fresh food products at harvest and cooling stages in a supply chain. In the model, they proposed different order quantities and transportation modes for the two separate stages to minimize the produce value loss. Lin and Chen (2003) developed a dynamic logistics control model for perishable product management, investigating the issue of how to allocate fresh food supplies to retailers with a given remaining shelf life of perishable products, expected sales and costs. The model maximizes profits under the condition of limited shelf life, uncertain supplies and demands, and costs incurred during a shelf life period.

Dynamic pricing itself is an independent area of inquiry and has been reviewed by Narahari (2005) in the context of *e*-business. Gallego & van Ryzin (1994) has provided a concise summary of different types of price differentiation and studied many examples of dynamic pricing and its connections with operational issues like inventory control. The research on inventory models that incorporate perishability or decay of the good are broadly classified into fixed life perishability models and random lifetimes models, as reviewed in Nahimas (1982). The majority of the literature in this area built on Ghare and Schrader (1963), who generalized the standard EOQ model to allow exponential decay. Cohen (1977) considered the case where the demand is the function of the price and assumed exponential decay. Rajan *et al.* (1992) tackled the question of how the inventory decay could affect price changes during the cycle.

The current RFID - related research has proposed new concepts, information structures, and control systems, which improve the agility and flexibility of business processes. Karkkainen *et al.* (2003) developed a prototype system that controls a large number of individualized deliveries of international projects to arrive at final sites just in time. They proposed a product - centric 'inside - out' delivery control approach with which products provide delivery requirements to the logistics service by RFID tags attached to the products. Liu *et al.* (2004) proposed a decentralized production control system with the RFID technology. Intelligent agents are integrated with the system to communicate with the products that bring the information to their own destiny. Through a simulation of different control rules, he concludes that, with the real - time information linked to products the agent - based model outperforms traditional control rules.

The existing research on perishable food products management has investigated impacts of product shelf life on costs and profits. Yet, the information accuracy and the way to obtain product value characteristics have not been discussed in sufficient details. The RFID technology provides the opportunity of automatic collection of product quality status based on key environment parameters that affect the product shelf life.

This research investigates the benefits derived from generating new business models or scenarios utilizing the automatic identification technology. We suggest that the information collected by the RFID system can be used to predict the demand in real time, adjust price dynamically to meet the demand, and maximize the profit. Hemachandra (2005) also considers inventory management and dynamic pricing using RFID technology for perishable good. But in his paper, the demand is discrete and has a known distribution .In contrasted, we adopt the product value concept in the pricing model to represent the impact of consumer perceived product quality on demands, consistent with Li and Tang (2006). The assumption is that the product value deterioration feature can be statistically established, which is beyond the scope of this paper. Important parameters, such as temperature and the length of time, will affect food values perceived by consumers in a retail store, but they can be easily captured in an RFID - enabled system. Thus, our model allows a quantitative investigation of the impact of pricing rules and ordering decision (enabled by the dynamic product tracing) on the management of perishable food in supermarket.

Ⅲ. The model

In order to extract the structural connection between time - varying costs and price in the presence of value decay, we consider a monopolistic retailer with inventory carrying costs. At the same time, the retailer is assumed to be facing a deterministic market demand that is a decreasing function of both the selling price and the drop value of time elapsed since the beginning of each inventory cycle. At the beginning of each inventory cycle, the retailer orders and stocks some quantity of the product which the market demand draws down to zero over the cycle, then another cycle starts.

1. Conceptualization and assumption

In our formulation, the time variable t is time elapsed since the last order was placed.

The retailer incurs two costs each time he/she places an order: a fixed ordering cost K which is independent of the order size, and a variable cost c for each unit ordered. Orders are assumed to be filled instantaneously. Let h be the per unit inventory holding cost per unit time. Let $p(t) > 0$ be the selling price per unit at time $t > 0$. Here $c, h, K > 0$. To measure the loss of product values, Blackburn and Scudder (2003) developed an optimization model based on evaluation of fresh food values. The research used exponential functions of time to indicate quick decreasing of the values over time:

$$V_t = V_0 e^{-\lambda t} \tag{1}$$

Where λ is a value deterioration parameter at time $t \ni [V_0 e^{-\lambda t}]$. V_t is the present value at time t. V_0 is the original value when $t = 0$.

Our research adopts the above expression of product value deterioration to trace and estimate product value losses over time. The maximum value of a product is assigned as 100 (%) at the beginning. To focus on the analysis of value tracing benefits and simplify the analysis, we take the demand in a determinative form in this research, so that an analytical expression of the optimal pricing can be generated. We adopt a widely used price - dependent linear demand description in the economic research literature as shown in equation (2) when we calculate the optimal ordering decision in section 3.3-3.5:

$$D(p,t) = \begin{cases} (a + V_0 e^{-\lambda t} - p)/b & 0 \le p \le a + V_0 e^{-\lambda t} \\ 0 & p > a + V_0 e^{-\lambda t} \end{cases} \tag{2}$$

Where λ is a value deterioration parameter, V_0 is the original value when t = 0. The demand rate per unit time is a function both of the dynamic price and the perceived value, which represents the food quality as the time elapses. While a price increase negatively affects demands, product quality or value has clear positive effects to demands.

For convenience, we define $P(t) = \sup p : D(p, t) > 0$ is the maximum dynamic price, and

$$D(p,t) = \begin{cases} > 0, & \forall 0 < p \le P(t) \\ = 0 & p > P(t) \end{cases} \tag{3}$$

Thus $P(t)$ is the maximum price the retailer would want to charge at time. We also define that

$$\tau = \sup\{t : P(t) \ge c + ht\} \tag{4}$$

τ is the point in time beyond which the unit contribution margin corresponding to the maximum price $P(t)$ is no longer positive. We denote V_e is the value with which consumers will stop purchasing the product. When $V_t = V_0 e^{-\lambda t} < V_e$, that is when $t > \frac{1}{\lambda}\ln\frac{V_0}{V_e}$, consumers will stop purchasing, and the demand is zero. Let θ is the cycle length (the time between orders) and Q the quantity ordered at the beginning of each cycle, which can be assumed to be constant over time, since the parameters of the problem do not vary from cycle to cycle. The cyclic pattern allows us to restrict our attention to the interval [0, θ]. Since the problem is deterministic, all the demand is met and inventory is zero at the end of each cycle. Thus, the ordering quantity Q is related to the demand $D(p,t)$ and the inventory denoted by $I(t)$ at time t as follows:

$$Q = \int_0^\theta D(p,t)dt \quad I(t) = \int_t^\theta D(p,r)dr \tag{5}$$

2. Optimal pricing with the product value tracing

We formulate the profit realized by the retailer in terms of the model parameters described above. The retailer's average profit per unit time, $\pi(p,\theta)$ is given by the revenue over a cycle, minus the purchase cost and the inventory holding cost over the cycle, minus the fixed cost per cycle, all divided by the cycle length:

$$\begin{aligned}\pi(p,\theta) &= \frac{1}{\theta}\{\int_0^\theta [p(t)D(p,t) - cD(p,t) - hI(t)]dt - K\} \\ &= \frac{1}{\theta}\{\int_0^\theta [(p(t)-c)D(p,t) - hI(t)]dt - K\} \\ &= \frac{1}{\theta}\{\int_0^\theta [(p(t)-c-ht)D(p,t)]dt - K\}\end{aligned} \tag{6}$$

The last equation is from (5) by exchanging the turn of the iteration. The average profit corresponding to an optimal policy $(\theta^*, p^*(\cdot))$ is given by:

$$\pi(\theta^*, p^*(\cdot)) = \max_{\theta, p(\cdot)} \frac{1}{\theta}\{\int_0^\theta [(p(t)-c-ht)D(p,t)]dt - K\} \tag{7}$$

Problem (7) can be solved in two stages. In the first stage, we find the optimal price as a function of t:

$$p^*(t) = \arg\max_p (p(t)-c-ht)D(p,t) \tag{8}$$

In the second stage, we substitute the optimal price given by (8) with the expression for optimal average profit given by (7), and solve for the optimal finite cycle length θ^*:

$$\theta^* = \arg\max_\theta \frac{1}{\theta}\{\int_0^\theta [(p^*(t)-c-ht)D(p^*(t),t)]dt - K\} \tag{9}$$

To optimize the price $p(t)$, the first and second order derivatives with respect to price are calculated from equation (8). We define $v(p, t) = (p(t) - c - ht)D(p, t)$, from the demand function (2), we can see that before the demand turns into zero,

$$\frac{\partial v(p,t)}{\partial p} = \frac{1}{b}[a + V_0 e^{-\lambda t} - 2p(t) + (c + ht)] \tag{10}$$

$$\frac{\partial^2 v(p,t)}{\partial p^2} = -2 < 0 \tag{11}$$

From equation (11), convexity of the profit function is proved. Let the first derivative be 0, we have the optimal price described as follow:

$$p(t) = \frac{a + V_0 e^{-\lambda t} + c + ht}{2} \quad \forall t \in [0, \min\{\tau, \frac{1}{\lambda}\ln\frac{V_0}{V_e}\}] \tag{12}$$

Form (12), we can see that:

$$\frac{dp(t)}{dt} = \frac{-\lambda V_0 e^{-\lambda t} + h}{2} \tag{13}$$

Thus, when $h > \lambda V_0 e^{-\lambda t}$, the optimal price is increasing with the time t; when $h \leq \lambda V_0 e^{-\lambda t}$, the optimal price is decreasing with the time t.

3. The optimal ordering decision

From (2) and (12), the demand under the optimal price is given by:

$$D(p^*(t),t) = \begin{cases} \frac{a + V_0 e^{-\lambda t} - (ht + c)}{2b} & t \in [0, \min\{\tau, \frac{1}{\lambda}\ln\frac{V_0}{V_e}\}] \\ 0 & otherwise \end{cases} \tag{14}$$

Next we will find the optimal cycle length from (9). We define

$$u(\theta,t) = \frac{1}{\theta}\{\int_0^\theta [(p^*(t) - c - ht)D(p^*(t),t)]dt - K\} \tag{15}$$

Form (12) and (14) above, we can calculate that:

$$u(\theta,t) = \frac{1}{\theta}\{\int_0^\theta \frac{(a + V_0 e^{-\lambda t} - (ht + c))^2}{4b} dt - K\} \tag{16}$$

Thus, the optimal ordering length cycle θ^* must satisfy the following condition:

$$\int_0^\theta (a + V_0 e^{-\lambda t} - (ht + c))^2 dt - \theta(a + V_0 e^{-\lambda\theta} - (h\theta + c))^2 - 4bK = 0 \tag{17}$$

An optimal order quantity can then be calculated from (5) ,(12) and (14):

$$Q^* = \int_0^{\theta^*} D(p^*(t),t)dt = \int_0^{\theta^*} \frac{a + V_0 e^{-\lambda t} - (ht + c)}{2b} dt \tag{18}$$

The optimal ordering length cycle θ^* is determined by the equation (17).

From the argument above, we can have the following proposition:

Proposition 1 Under the condition we assume above, the optimal pricing with the product value tracing is given by (12), the optimal ordering length cycle θ^* must satisfy (17), and the optimal order quantity is given by (18).

4. The fixed pricing without the product value tracing

When the retailer must choose a fixed price, we can see that the profit function is given by:

$$\pi(p_f,\theta)=\frac{1}{\theta}\{\int_0^\theta[(p_f-c-ht)D(p_f,t)dt-K\} \quad (19)$$

If he/she does achieve a positive profit, then the cycle length θ_f and the price p_f which maximize $\pi(p_f,\theta)$ must be solutions of the system of equations:

$$\frac{\partial\pi(p_f,\theta)}{\partial p}=0 \quad (20)$$

$$\frac{\partial\pi(p_f,\theta)}{\partial\theta}=0 \quad (21)$$

If the demand function is the same as given by (2), then from the first order condition (20),we can get the optimal fixed price :

$$p_f=\frac{\int_0^\theta(a+V_0e^{-\lambda t}+c+ht)dt}{2\theta} \quad (22)$$

the average profit at this price for a cycle of length θ_f is:

$$\pi(p_f^*,\theta)=\frac{[\int_0^\theta(a+V_0e^{-\lambda t}+c+ht)dt]^2}{4b\theta^2}-\frac{\int_0^\theta(a+V_0e^{-\lambda t})(c+ht)dt}{b\theta}-\frac{K}{\theta} \quad (23)$$

The optimal cycle length θ_f is the unique solution of:

$$\frac{\partial\pi(p_f^*,\theta)}{\partial\theta}=0 \quad (24)$$

Based on the argument above, we develop the following proposition:

Proposition 2 Under the condition we assume above, the optimal fixed price without the product value tracing is given by (22), the optimal ordering length cycle θ^* must satisfy (24).

5. Optimal pricing with the product value tracing vs. fixed price

We can compare the profit between the fixed and dynamic price cases for a fixed cycle length.

From equation (16), we can see that the profit with the product value tracing is:

$$\pi(p^*(\cdot),\theta)=\frac{1}{\theta}\{\int_0^{\theta}\frac{(a+V_0e^{-\lambda t}-(ht+c))^2}{4b}dt-K\} \quad (25)$$

From equation (23), we can see that the average profit with the fixed price is:

$$\pi(p_f^*,\theta)=\frac{[\int_0^{\theta}(a+V_0e^{-\lambda t}+c+ht)dt]^2}{4b\theta^2}-\frac{\int_0^{\theta}(a+V_0e^{-\lambda t})(c+ht)dt}{b\theta}-\frac{K}{\theta} \quad (26)$$

Thus, by calculation, we can get the difference between the profit with the product value tracing and the fixed price for a fixed cycle length:

$$4b\theta^2[\pi(p^*(\cdot),\theta)-\pi(p_f^*,\theta)] =$$

$$\theta\int_0^{\theta}(a+V_0e^{-\lambda t}+ht+c)^2dt-[\int_0^{\theta}(a+V_0e^{-\lambda t}+ht+c)dt]^2 \quad (27)$$

Now, we let

$$f(t)=a+V_0e^{-\lambda t}+ht+c$$

$$F(\theta)=\theta\int_0^{\theta}f^2(t)dt-[\int_0^{\theta}f(t)dt]^2$$

Then,

$$F(0)=0$$

$$\frac{dF(\theta)}{d\theta}=\int_0^{\theta}(f(t)-f(\theta))^2dt\geq 0 \quad (28)$$

From (28), we can see that equation (27) is not negative. Therefore, we have the following proposition:

Proposition 3

For a fixed cycle length, under the condition we assume above, the profit with the product value tracing is lager than the profit which is given by the fixed optimal price.

Ⅳ. Conclusion

As the food safety and quality become a legal responsibility, more attention is being paid to the management of perishable. With the transparent and accurate product value information becoming increasingly available in a supermarket, consumers make their purchasing decisions based more on the real time product value characteristics rather than price. The paper proposed a model to determine optimal pricing on the real time and optimal ordering quantity for perishable products. We showed that larger profit can be achieved by using the product value tracing than using fixed optimal price for a given cycle length.

This model can be implemented in the management of perishable food. For supermarkets, it is crucial to price products based on the identified product value so that optimal sales can be achieved and profits can be maximized. When the supermarket sells the milk or some fresh vegetable, when the duration is becoming, it will sell this food at very low price in order to avoid the loss to the best of its ability. Sometimes, it will use these approaching duration milk as a way of promoting by giving the consumers free. But this method is not the optimal from our model. We can change the price in real time rather than change the price when the duration is approaching. This method is also suggested by Tsiros, M. Heilman (2005).And our model further suggests how to give the optimal price in real time.

With the use of RFID technology, some interesting mathematical models for inventory management and pricing can be applied in practice. For example, in the timing of discount offered, if the age of all available items is known, then decisions regarding quantity to be ordered can be taken by use of this model. Most of the present literature does not give any mathematical basis to justify the use of RFID technology in particular applications. Also, the implementation of such systems should be based on the long term goals of the organization, while keeping an eye on possible technological developments in these fields. More studies are needed to investigate relationships between perceived product values and demands. Another research area is the implementation aspects of the RFID technology with the proposed supply chain scenario, which will allow the comparison of the performance of the RFID with other technologies including barcode systems.

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