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Perishable inventory management and dynamic pricing using RFID technology

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Abstract. In price-sensitive markets, price promotions coupled with an appropriate item replenishment strategy can be effective in controlling the total costs of servicing the market. In supply chains that handle perishable products, inventory management is already a complex problem and the management of products in a dynamic-pricing environment is even more challenging. Monitoring and control of time-sensitive products can be facilitated by the application of radio frequency identification (RFID) technology, which enables non-contact, real-time data collection and efficient interfacing with the management control system in the supply chain. This paper describes an integrated framework for inventory management and pricing in a discrete time (periodic review and ordering) framework, and describes an efficient algorithm, including a new approximation, for the related optimization problem. We then propose a suitable architecture for the application of RFID technology in this context, to realize the potential benefits.

Keywords. Perishable inventory management; radio frequency identification; value chain; dynamic pricing; dynamic programming; product withdrawal; price promotions.

1. Introduction

Controlling inventories is an important aspect of supply chain management. Managing inventories of perishable products is difficult because of their limited shelf lives. The fixed-life perishability problem (FLPP) requires a multi-dimensional inventory vector to account for the age profile of items, while calculating an optimal inventory policy. Due to perishability, there is an additional cost of disposal of outdated items, and this can also lead to out-of-stock situations, if not managed effectively. An alternative to avoid outdating is to lower the prices of items to stimulate increase in demand. Another reason for lowering the prices of items is change in the technology or new product introduction by a competitor which is superior to

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an existing product. This is needed to ensure that the manufacturer does not incur loss due to deterioration of the items or due to its withdrawal from the market. Price promotion is known to be an effective tool where there is demand elasticity (Lilien *et al* 1999).

The problem considered here is the following: in every period, whether to promote the price or not and to determine the optimal ordering quantity. The product considered is a perishable one, which has to be withdrawn from the market after a finite horizon. The various costs considered are ordering cost, holding cost, shortage cost and cost of deterioration. If there is price promotion, there is a fixed cost of promotion in each period. It is assumed that once a product is promoted, it will remain promoted till the end of the horizon. Based on the elasticity of the demand, we assume some demand distribution for the price promoted situation, as also a demand distribution for the normal case without price promotion. Many variant scenarios can be modelled in our framework, in addition to the one just described.

Our algorithm for the control of inventories relies on monitoring of the age-wise profile of inventory in every period. This is now possible, realistically speaking, with the introduction of RFID technology, as we discuss below. Computationally speaking, this results in a large state space that makes the dynamic programming formulation difficult to implement, especially in the stagewise optimization step. This is addressed by a new approximation where we collapse some inventory vector components.

The availability of real-time data has a major influence on the optimal ordering quantity and the optimal time of promotion decision. An information system, viewed from an infrastructural and managerial perspective, has various elements such as identification and collection of relevant data elements, communication and processing of the data at regular intervals etc. (Raghuram & Rangaraj 2003). RFID technology is an emerging trend in this field and is mainly used for product identification, collection and communication of relevant data. This paper considers an RFID-based methodology for inventory control of perishable products and price promotions. RFID technology requires very little or no handling of items and is therefore well suited for inventory control of perishable products. The technology also helps in updating the inventory status in real time without product movement, scanning or human involvement.

The paper is organized as follows. This section surveys the literature on perishable inventory control, and some models on price promotions. It also includes some relevant literature on RFID technology. The next section explains the background for inventory management in the context of perishable inventory along with the need for dynamic pricing. Section 3 explains the fixed-life perishability problem. Section 4 focuses on RFID systems and their impact on the value chain. In §5, an RFID-based architecture for managing perishable inventory and the associated pricing problem is described.

1.1 *Literature review*

1.1a *Perishable inventory management:* The objective of perishable inventory management is to obtain optimum returns considering the useful life of the product. In the literature, inventory models have been formulated for perishable products subjected to the various demand conditions and life considerations. When the life of the product is just one period, the problem reduces to the well-known 'newsvendor' problem. When demand is random and product lifetime exceeds one period, determining ordering policies is difficult since various states of deterioration (or ages) of product must be known in each period; in short the state vector of inventory must include the age-wise profile. Goyal & Giri (2001) have surveyed the literature on problems of various types, to do with decaying, fixed-life and random life of items. Nahmias (1974) and Fries (1975) have analysed fixed-life perishable inventory problems under various conditions. Weiss (1980) presents the problem in a continuous review framework, considering all costs concerned with ordering, holding, shortage, disposal, penalty and revenue in lost sales and backordering cases. For the lost sales case he identifies a continuous review $(0, S)$ policy and for the backordering case a continuous review (s, S) policy in the case of linear shortage cost, as optimal policies.

Apart from determining optimal policies for ordering, the literature in this area has also addressed relevant marketing decisions based on consumer preferences. Abad (2003) considered the problem of dynamic pricing and lot-sizing for a reseller who sells perishable goods. Also the price of the product can be varied within the inventory cycle to take into account the age of the product and the value drop associated with it. Adachi *et al* (1999) in their paper propose a perishable inventory model with consideration of different selling prices of perishable commodities under stochastic demand. In their model, different lifetimes of perishable commodities are provided, and they considered the possibility of discriminating selling prices for products of different lifetimes.

In another model by Luo (1997), the impact of marketing strategies such as pricing and advertising, as well as backordering decisions on the profitability of the system is studied. The model aims at finding the optimal order quantity and order up to level where the demand is a function of advertisement and price elasticity. The method used to find the values is an exhaustive search procedure. The model shows that marketing decisions such as price and advertisement frequency had a significant impact on the profitability of the system.

Chiu (1995) formulated a continuous review perishable inventory model based on approximations for the expected outdating, the expected shortage quantity and the expected inventory level. He developed a (Q, r) ordering policy under a positive order lead time when the objective function is minimization of the total expected average cost per unit time. Nahmias (1977, 1982) has formulated approximations for several complex stochastic inventory models. The approximations are formulated for both periodic as well as for continuous review of the inventory.

1.1b *RFID technology:* Bhaskar & Mahadevan (2004) have explained the applications of RFID technology to various fields including inventory management. RFID can be applied to collect information in various segments of the supply chain. Karkkainen (2002) explains how RFID technology affects the retail sector and the benefits of the deployment of the such technology across the supply chain. Implementation issues of RFID technology in the retail segment has been discussed by Yao & Carlson (1999). McFarlane *et al* (2003) show that automatic identification (Auto ID) technology is advantageous in the manufacturing sector also. Walmart, a retailing giant has already taken steps towards RFID technology by asking its major suppliers to adopt RFID for case and pallet-load shipments by January 2005[1]. Hellstrom (2004) in his technical report analysed how and why various packaging logistics activities in retail supply chain would be affected by the application of RFID technology in the packaging.

2. Background for modelling

2.1 *Inventory control*

In our framework, inventory control refers to monitoring the availability of material, assigning it to demands that have arrived and placing orders for replenishment of the product. All

[1]Anon 2005 WalMart Begins RFID Rollout. *RFID J.* available at
http://www.rfidjournal.com/article/articleview/926/1/1/

these activities may not happen continuously, or even in all time epochs. Inventory control is employed in the context of "pull-based" or replenishment-based systems where the trigger for placing an order is the current inventory status which in turn is related to the demand for items in recent periods. Inventory is a major investment in most of the companies. It strongly influences the internal flexibility of the organization, e.g., by allowing production levels to change easily and by providing good delivery performance to the customers. Inventory costs include working capital and storage space costs as well as costs to do with obsolescence, deterioration and loss.

In recent years, attention in the manufacturing industry has concentrated on customer demand-driven systems. In retailing, inventory management attempts to provide high demands and high profits to the company as well as good services and fresh items to customers at low cost. Inventory models are commonly used to determine when and how much to order while optimizing the overall organizational goal, i.e., maximizing the net profit.

Our analysis refers to perishable as well as potentially obsolete products. Perishability refers to the decrease in value or usability of the product over time due to the inherent characteristics of the product. If the rate of deterioration is sufficiently low, its impact on the modelling of such inventory systems can be ignored. Perishable products due to their nature impose an additional constraint of shelf life in the modelling of such inventory systems. The maximum useful life of the product is the shelf life. An item can also be lost because of obsolescence. Obsolescence in our case, happens because of the introduction of new products, by the organization or its competitors. In fact, in the illustrative examples, the product is seen to have a stable market (as characterized by stationary demand), but is withdrawn by the organization for strategic reasons of staying technologically current.

2.2 *Dynamic pricing*

Dynamic pricing, in general, is the assignment of different prices to the items of the same product category, considering the individual characteristics or the changes of the product status. In this paper, for concreteness, a restricted type of dynamic pricing is considered, where a fixed promotional price can be introduced at the beginning of a period and once introduced, continues to the end of the horizon. This is done in the context of a finite horizon dynamic programming which involves withdrawing of the item at the end of a stipulated period.

A retailer faces the challenge of dealing with understocking and overstocking in the face of supply and demand uncertainties. Understocking of the items is generally more undesirable as there is loss of goodwill of the customer and also loss of future demands. Overstocking leads to some extra storage costs and perhaps obsolescence or disposal cost at the end of horizon. An alternative to avoid the disposal of items is to put older items on sale, with lowering of prices to induce demand.

Such a dynamic pricing system requires the identification, location, and precise age-profiling of items. With traditional systems these processes are carried out manually and therefore are error-prone and time-consuming. RFID technology provides the required information in a dynamic manner. This would allow the retailer to dynamically adjust prices with respect to demands and stock levels and maximize the revenue. Dynamic pricing together with the internet and web-enabled applications has been used in airline industries. In retailing, RFID technology together with the internet can help real-time decision-making.

For products like food, perishability can be controlled to some extent by using sophisticated storage technologies, perhaps involving higher inventory-related costs. On the other hand for FMCG products, fashion goods and electronic items, the life of product depends on external factors such as technological advancement, new product introduction by competitor, seasonal changes etc. In some cases, the product is withdrawn from the market after some fixed time, such as seasonal goods e.g., toys, or as a strategy to remove old versions in order to promote newer versions of the product e.g., electronic items. We consider cases where there is a need to derive optimal policies which consider deterioration as well as obsolescence, with the option of price promotion. Promotion can also be achieved by advertising, price discounting, coupons, gift with purchase etc., which are in a sense equivalent to price promotion.

Dynamic pricing, by itself, is a topic of independent interest, and has been reviewed in a companion paper in this volume (Narahari *et al* 2005), in the context of *e*-business. This has a concise summary of different types of price differentiation, many examples of dynamic pricing and its connections with operational issues like inventory control in this context (e.g. Gallego & van Ryzin 1994). Another related area where dynamic pricing is important is that of yield management, in industries like airlines (e.g. Feng & Gallego 1995). Here, the tradeoffs are of a different type, capturing capacity utilization (rather than inventory holding) versus shortage and obsolescence costs.

3. Fixed-life perishability problem (FLPP) under price promotions

The problem studied by Konda *et al* (2003) is the possible introduction of price promotion over a finite horizon, along with a periodwise ordering policy in the case of a perishable product with a fixed-life of L periods. The decision variables are (a) an indicator variable which indicates whether to price promote or not, and (b) the optimal ordering quantity in each period. We consider scenarios where once the product is promoted, it continues to be so till the end of the horizon. This is not, however, a crucial assumption in our framework, and other possibilities can be modelled easily. It is assumed that demand is fulfilled by the first-in-first-out (FIFO) rule, as this will reduce the number of units that will perish. All items up to their shelf life are assumed to be of equal value to the customer and will command the same price, when sold.

Let $r(s_t, (a, y_t))$ be the one-period expected reward in the tth stage for the action (a, y_t) in state s_t; we represent state s_t by $(x_{1t}, x_{2t}, \ldots, x_{Lt})$ which is the inventory vector at the beginning of period t, where, x_{it} is the number of units in period t having remaining shelf life of i periods, $i = 1, \ldots, L$ and $t = 0, \ldots, N$, where N is length of planning horizon. The value of a is either p (if promotion is offered) or n (if promotion is not offered). Let y_t be the ordering quantity in any period t. D denotes the maximum demand, u_{ta} the random variable of demand in period t with known distribution when decision a is made, I the maximum inventory and i_t the total inventory on hand at the beginning of period t, and j_t the initial inventory on-hand which is transferred from period $t-1$ to t. The fixed cost of promotion is K_a which is incurred in the periods in which the product is promoted.

The reward in each period $r(\cdot, \cdot)$ takes into consideration the selling price of each item R_a, linear ordering cost of c per unit ordered, holding cost of h per unit per unit time, shortage cost of s per unit short, and deterioration cost of b per unit. The one-period expected reward is given by

$$r(s_t, (a, y_t)) = \sum_{k=0}^{D}[pr(u_{ta} = k)\{G(a, y_t) - (h[i_t - k]^+) - (b[x_{1t} - k]^+)\}] - K_a, \quad (1)$$

for $t = 0, 1, 2, \ldots, N-1$, where

$$G(a, y_t) = \{(R_a \cdot \min[k, i_t]) - (s[k - i_t]^+) - [y_t \cdot c]\}, \tag{2}$$

where $[a]^+ = \max(a, 0)$.

Our objective here is to maximize total expected reward over the horizon. Let the maximum total expected reward from state s_t in period t till the end of horizon be $Q_t^*(s_t)$. We are interested in finding $Q_0^*(s_0)$ for all initial states s_0. The optimal policies can be found by using the approach of backward induction (Puterman 1994; Bertsekas 1995). This framework of multi-stage dynamic programming is also called a Markov decision process (MDP). The optimal reward can be calculated by backward induction as follows.

The reward for the state s_N in the last period N, for any action (a, y_N) is

$$Q_N^*(s_N) = \max_{a,\ y_N = 0,\ldots,\ I - j_N} \left[\sum_{k \in [0, D]} [pr(u_{Na} = k)\ \{G(a, y_N) - [b[i_N - k]^+]\}] \right]. \tag{3}$$

The maximum total expected reward in state s_t, from period t to the end of horizon is given by the following equation, where $t = 0, 1, 2, \ldots, N-1$,

$$Q_t^*(s_t) = \max_{a,\ y_t = 0,\ldots,\ I - j_t} \left\{ r_t(s_t, (a, y_t)) + \left[\sum_{s_{t+1} \in S, k \in [0, D]} \begin{bmatrix} [pr(u_{ta} = k)]^* \\ [Q_{t+1}^*(s_{t+1})] \end{bmatrix} \right] \right\}. \tag{4}$$

At the end of this procedure, we have an optimal Markov deterministic policy, $\pi = \{(a_0, y_0), \ldots, (a_N, y_N)\}$, which indicates the control (ordering and promotion) actions to be taken for the sequence of states that are visited. Here, s_{t+1} is the resulting state in period '$t+1$', $pr(u_{ta} = k)$ is the probability that demand in any period t is k, when action a is taken and S is the state space of the beginning inventory vectors. The second term of (4) gives maximum expected reward till the end of the horizon through period $t+1$. Equations (3) and (4) are solved recursively (Puterman 1994; Bertsekas 1995) for a particular value of inventory vector, demand distribution and other cost parameters.

The following example (tables 1 and 2) is used for illustration. Consider a system with a product life of 4 periods, starting from a time where the length of the horizon is 6 periods (meaning that the product is withdrawn at that time). The demand distribution is given in table 1 (we notice that price promotion results in higher expected demand, in the example). Let cost per item be Rs. 80, shortage cost per item be Rs. 15, holding cost per item per period be Re. 1, deterioration cost per item be Rs. 80 and fixed cost of promotion be zero (the next example has a non-zero fixed cost). The selling cost of the item when promoted is taken to be Rs. 96 and when not promoted is taken to be Rs. 120.

Table 1. Probability distribution of demand in every period.

Demand units	0	1	2	3	4	5
Promoted	0·05	0·05	0·3	0·4	0·1	0·1
Not promoted	0·1	0·1	0·5	0·1	0·1	0·1

Table 2. A part of the lookup table for the actions suggested (promotion or otherwise and ordering quantity) for those states in which price promotion is not done till period t.

	Time period t					
Inventory vector	1	2	3	4	5	6
2 0 0 0	N-3	N-3	N-3	N-3	N-2	N-0
3 0 0 0	N-2	N-2	N-2	N-2	P-2	P-0
4 0 0 0	N-1	N-1	N-1	N-1	P-1	P-0
5 0 0 0	N-0	N-0	N-0	N-0	P-0	P-0
1 1 1 0	N-2	N-2	N-2	N-2	N-0	P-0
3 1 1 0	N-0	N-0	N-0	N-0	P-0	P-0

Table 2 gives some of the representative inventory vectors with their ordering quantity and promotional decision in the periods ranging from first (start of the horizon) to the sixth (end of the horizon). The inventory vector [3 1 1 0] for example, indicates three units of products with one period of life remaining, one unit each of product with two and three periods of life remaining and zero units with four units of period life remaining. Periods are represented row wise starting from first period of the horizon to the last period of the horizon. We use the following notation:

- P: Promotion and N: No promotion
- If the inventory status [3 0 0 0] is encountered in the 4th period, the policy N-2 suggests "no promotion" and ordering of 2 units.

Recall our assumption that if in period t a price promotion is announced, then the product continues to be in promoted state for all the remaining periods till the end of the horizon. Table 3 gives a part of the lookup table for those states that might be encountered after price promotion.

3.1 *An illustrative example with a sample path*

In this section, the path followed by the total inventory subjected to the variation of demand is explained with an example. Let, $L = 4, c = 40, b = 20, R_n = 70, I = 6, s = 15,$

Table 3. A part of the lookup table for the action suggested (ordering quantity), assuming price promotion in the current period or earlier.

	Time period t					
Inventory vector s_t	1	2	3	4	5	6
2 0 0 0	3	3	3	3	2	0
3 0 0 0	2	2	2	2	2	0
4 0 0 0	1	1	1	1	1	0
5 0 0 0	0	0	0	0	0	0
1 1 1 0	2	2	2	2	1	0
3 1 1 0	0	0	0	0	0	0

Table 4. Probability distribution of demand in every period.

Demand units	0	1	2	3	4	5	6
Promoted	0·0	0·0	0·0	0·2	0·2	0·4	0·2
Not promoted	0·2	0·2	0·4	0·2	0·0	0·0	0·0

$K_p = 20$, $N = 10$, $D = 6$, $h = 1$, $R_p = 54{\cdot}3$, the notation is the same as discussed in the earlier section. The demand distribution is as shown in table 4.

A typical sample path (representing the total inventory) is shown in figure B1 of appendix B along with the sequence of decisions for this sample path (table B1). In figure B1, as an example, the initial inventory vector in 4th period is [1 0 0 0] and the decision in 3rd period is not to promote. The optimal decision in the 4th period as read from table B1 is "not to promote" and to order 2 units. The demand vector from 4th to 9th period is (4 1 0 0 4 3), represented by μ_i, where, $i = 4, \ldots, 9$. The state is represented by an inventory vector at the beginning of the period and promotional decision in that period; N for no promotion and P for promotion. For example, in 7th period the inventory vector is [0 2 1 0] and the decision is "not to promote". In the next period, the recommended decision is to promote and order 3 units.

3.2 *Observations*

Some observations made are as follows (Konda *et al* 2003).

- For the same total inventory, the distribution of inventory of different ages influences the policy. Compare the optimal policies for the vector [3 0 0 0] and [1 1 1 0] in table 2. Broadly speaking, a position with relatively "fresh" inventory [1 1 1 0] suggests no price promotion, while an inventory position with a large amount of anticipated outdating [3 0 0 0] will suggest promotion. This is explored further by Chande *et al* (2004) by formulating the definition of adverse vectors as a way of ranking or ordering different state vectors.
- The results are sometimes counter intuitive, at least on the face of it, such as the policy, P-2 for [3 0 0 0], which suggests promotion as well as ordering. This is because of the fixed cost of promotion and, if the decision taken is to promote, then there is a trade-off on the expected higher profits from sale.
- Within a certain decision (say, no promotion), the order-up to level decreases as the number of periods to the end of horizon approaches. This tapering effect is well-known for non-perishable products.
- If at epoch t an inventory vector suggests promotion, then at any epoch $k \geq t$ the same inventory vector also suggests promotion. This is because the risk of losing the inventory is more towards the end of the horizon.
- As expected, higher holding cost and higher deterioration cost tend to make the manufacturer announce price promotions. Higher shortage costs lead to increase in the replenishing quantities.

3.3 *An approximation algorithm*

In our model, the state space includes the age-wise profile of inventory. For longer life items, the size of the state space also increases and leads to the increased complexity of the model.

Table 5. Average percentage error for different reduced shelf lives.

Actual shelf life	Actual Inv. vector	Approx. shelf life	Approx. Inv. vector	Avg. % Error
2	(1, 2)	2	(1, 2)	0
3	(1, 1, 1)	2	(1, 2)	2·172
4	(2, 0, 2, 1)	2	(2, 3)	12·094
6	(2, 0, 0, 2, 0, 1)	2	(2, 3)	12·525
4	(1, 0, 0, 1)	4	(1, 0, 0, 1)	0
5	(0, 0, 0, 1, 2)	4	(0, 0, 0, 3)	1·532
7	(0, 0, 0, 0, 0, 1, 2)	4	(0, 0, 0, 3)	1·921

A key observation is that the optimal ordering quantity is more sensitive to changes in the older inventory than in the newer inventory. This is the basis for an approximation to the state space that we discuss below.

In an extension to Konda's work, Chande *et al* (2004) have shown that the expected reward function is concave in ordering quantity for any fixed beginning inventory vector in any fixed period and that then a base stock policy is optimal. They propose an approximation to the problem whereby a dynamic program of reduced dimension is formulated. Here, the state space of inventory vectors representing inventory of various ages (say L, the life of the product), is represented by an inventory vector of smaller dimension (say r). The last component of the vector contains all items that are relatively fresh (i.e. which will not perish in next $r-1$ periods). This idea of grouping the fresher inventory is similar to the one used by Nahmias (1977). For example, the beginning inventory for six periods of life, $(x_1, x_2, x_3, x_4, x_5, x_6)$, can be approximated to $(x_1, x_2, x_3, \sum_{i=4}^{6} x_i)$. It is observed that a value of r equal to 4 gives a suitable approximation to higher life problems in most situations (see table 5).

Nahmias (1982) has also formulated other approximations for perishable products with fixed-life over a finite horizon. He has attempted to construct policies of the order-up-to type (critical number policies), which are based on the total inventory. To do this, he has approximated the expected outdating quantities as well as the related costs of outdating by a combination of upper and lower bounds, and eventually their arithmetic average. The inventory balance equations are also suitably approximated. This scheme seems to work well in the examples he reports.

We use the first type of approximation which works well in our context, and show that it holds even for the case of product promotion combined with inventory control.

The average percentage error is average taken over the next 10 periods of the percentage difference between the actual reward and reward after approximation. As seen from table 5, for 2 period shelf life approximation the average percentage error increases for longer life items. However, the approximation of 4 life periods works well for longer life items also. Even for the small example in §3, the approximation is useful because the size of the state space of inventory vectors is 252 if the shelf life is 5 periods, whereas it is 126 if the shelf life is approximated with a shelf life of 5 periods.

As can be seen from figure 1, the average percentage error for the approximation model is within 1% if we use a shelf life of 4 periods. The savings in computational time are significant, as the state space dimension reduces. The expected reward is over 10 periods for some particular starting inventory vector.

The following are some observations based on our approximation algorithm.

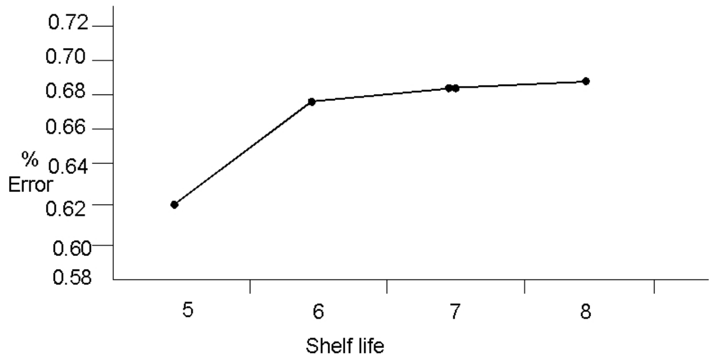

Figure 1. Percentage error in total expected reward for different shelf lives if a shelf life of 4 periods is used.

- The approximation is seen to be quite accurate for the total reward estimation, for unimodal demand distributions. However, even when the error in the reward term is higher, both the optimal ordering quantity as well as the promotion decision seem to be calculated correctly, in all our examples. Therefore, the approximation is quite robust in terms of the optimal policy.
- Deterioration with the approximated vector is an overestimation of the true value.
- Error in expected reward when using the approximation increases with increase in shelf life but the rate of increase in the error decreases. Error in approximation lies in the range of 0–4% for the per period reward.
- Distributions with low coefficient of variation give lesser error as compared to ones with higher coefficient of variation.
- In actual implementation, the entire age profile has to be updated in every period without collapsing the inventory states. The approximation is used in the optimization phase of the DP to reduce the search space, thereby reducing computational time significantly.

A detailed description of the approximation algorithm is given by Chande *et al* (2004). The above fixed-life perishability problem (FLPP) takes as input data, a variety of cost parameters such as holding cost, ordering cost, shortage cost, outdating cost and, in the case of price promotions, advertising cost and fixed cost of promotion. As usual, the inventory policy algorithm also requires the specification of the stock on hand at any point in time, and the demand distribution based on past data.

The next two sections present a schematic view of the potential for RFID technology in the context of perishable inventory management.

4. RFID systems and their impact on the value chain

The success of an enterprise applications depends on the availability of accurate information in the required format at the right time. The various tools used for the information collection are manual data collection, machine vision, bar coding technology, and RFID (radio frequency identification) technology (Mandal & Gunasekaran 2002). Each of these techniques has certain benefits and limitations as regards human intervention, labour, range of application, cost and accuracy. Systems such as RFID are meant for the automated retrieval of the identity of objects while they move through the supply chain. Some technological and operational aspects of RFID technology are given in appendix A.

To varying extents, techniques prior to RFID are labour-intensive, expensive, error-prone and also unable to ensure that the information provided is up-to-date. In comparison with bar-code systems that involve manual scanning and identify one object at a time, RFID systems use tags and readers that do not require line-of-sight for reading. Within the reading range of a wireless reading device, it is possible to automatically read hundreds of tags per second. The application of RFID technology may provide substantial efficiencies at operational level because of its ability to collect and consolidate real-time data. An RFID system overcomes some of the limitations of bar-code technology as well as those of other traditional systems and thus seems to be a reasonable option, more so with continuous research aimed at reducing the cost of such systems (Sarma *et al* 1999).

4.1 *Impact on the value chain*

Many industries now use enterprise solutions such as supply chain management (SCM), enterprise resource planning (ERP) etc. These applications maintain data and their flow across the functional areas of the organization. The IT infrastructure of companies having integrated databases can be directly connected to RFID systems for data retrieval. Web-enabled applications such as information about product availability, variety, price etc. can qualitatively enhance customer service. Such applications require faster and quicker response from suppliers. RFID technology can be effectively used for such applications to dynamically update the information. It has been shown that enterprise applications, such as SAP or Warehouse Management System (WMS), can be configured and linked to other hardware devices, including an RFID system for direct and on-line collection of data for operational and management use (mandal & Gunasekaran 2002).

As shown in figure 2, the various segments of a typical supply chain are supplier, manufacturer, distributor, retailer and consumer (Raghuram & Rangaraj 2003). In a supply chain, data inputs include transactions associated with receiving of material, storage, location, picking, inspection and ordering. To manage the supply chain, one needs a total control of these activities, and this crucially depends on the real-time visibility of the activities at all the segments. The processing of data is relative to the movement of the product. The requirement is for the right amount of data at the right time, on real-time basis.

Although industries are using sophisticated enterprise applications, many of these have not been truly successful in managing complex supply networks. One basic reason for this is that they use traditional methods for information retrieval. Information collected by these methods lacks real-time visibility. RFID technology is one of the data collection techniques

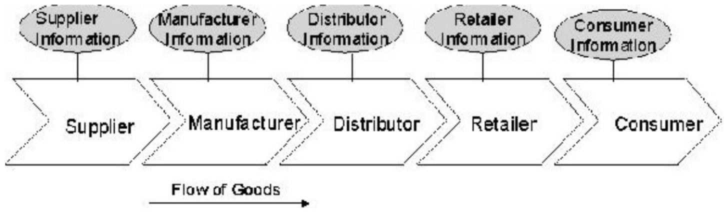

Figure 2. Flow of goods in a supply chain.

capable of providing up-to-minute information of each segments of the supply chain. RFID technology, if deployed successfully in a supply chain, would be beneficial for each of its segments.

The benefits of using RFID technology for a manufacturer includes time and cost savings in assembling and dispatching of finished products because of the automation in receiving and tracking of parts. For a distributor/retailer, RFID technology gives a complete inventory profile of the store and this in turn helps in taking appropriate actions in case of low/excess inventories. Also by providing an age-wise profile of the inventory, it helps in usage of proper issuing policies, like FIFO and (occasionally) LIFO. With RFID technology it is also possible to track an item after selling; say, as a part of after-sales service or recycling.

Therefore, the real benefits of RFID deployment will follow only if RFID technology is properly integrated with existing information systems in the supply chain. In order to achieve these benefits from RFID deployment, companies must tie in RFID data tightly with enterprise applications.

5. Perishable inventory management with RFID technology

Inventory control requires keeping track of the products to determine the demand and decide various control parameters, (such as the ordering quantity and the promotion decision in our case). Effective inventory management depends upon the effective use of data in the organization's information system.

With RFID technology, inventory can be updated in real-time without product movement, scanning or human intervention. A fully automated system allows the inventory status to be determined automatically and can be used to monitor product levels at pre-defined intervals. In a replenishment-based system, whenever the total inventory drops below a certain level, the system could place an automatic order, either at the warehouse or manufacturing stage in the supply chain.

On the retailing side, RFID at the point of sale can be used to monitor demand trends or to build a probabilistic pattern of demand and can be used in appropriate inventory planning models.

5.1 *An RFID-based architecture for management of perishable inventory*

It is clear that for the model discussed in §3 to work, the current state of system, comprising the age profile of inventory on hand and state of promotion decision, is needed. Also required is the current period of the planning horizon. In every period, the current profile of items and their age is required to derive an optimal inventory policy and marketing decisions such as pricing. A RFID-based support system for managing perishable inventory to implement inventory control and pricing decision is described below.

Typically, an RFID tag, apart from the manufacturer code and the product code, contains a serial number specific to each pallet or case or individual product, depending on the level of granular implementation of the tagging. In our proposed scheme, we assume that the RFID tag information can be processed to infer the date of manufacture. From this, and using the product information and the current clock time, the useful life of the product (in calendar time) and therefore the age profile of the total inventory at the appropriate location can be determined. The tag is alive till the product is sold at retailers or the product has deteriorated

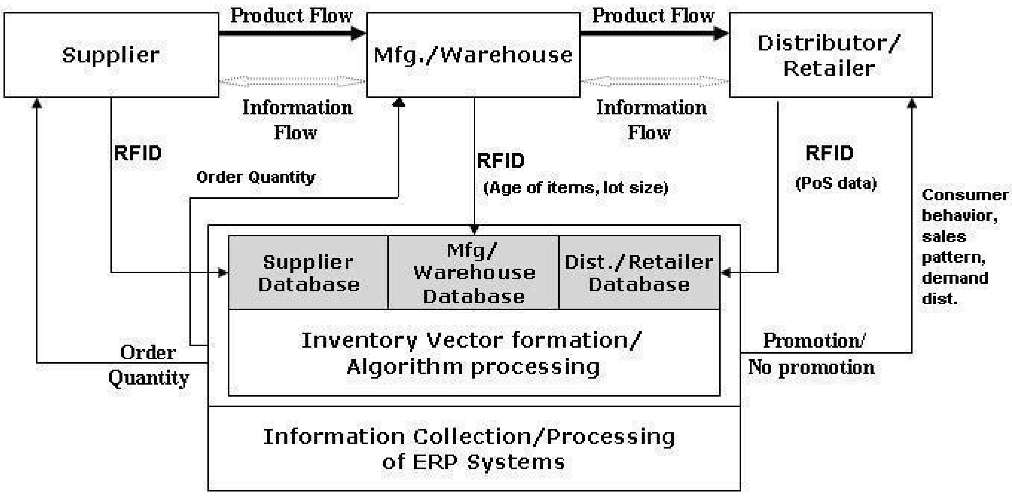

Figure 3. An RFID-based architecture for management of perishable inventory.

(end of the shelf life). The tag can then be deactivated or reused in case of reprogrammable tags.

Therefore, a key element in our implementation model is a central processor that collects the above information and computes the state of model $(x_1, x_2, \ldots, x_L, a)$. Such RFID-based systems having a central processor are described in Yao & Carlson (1999) in some detail. In the next step, this central processor uses either the algorithm described earlier, or approximation of it to decide the amount to order and the decision regarding promotion, if required.

A schematic diagram of a multi-stage version of this system is shown in figure 3. As shown in the figure, product availability at the supplier, manufacturer and distributor/retailer is available through a central processing system (or host computer). The major player of the supply chain is assumed to be the manufacturer in this architecture. Each product is individually identified along with its status. This data from all sources, i.e., from manufacturing warehouse and distributor/retailer warehouse (and product identification at supplier if necessary) is communicated by wireless transmission to the host computer through RFID units (not shown in the figure). The host computer or central processor can perform the operations based on the aggregated data and form the inventory vectors. These vectors can be then used to compute optimal delivery including ordering quantity and promotional decision. These decisions are then conveyed to respective supply chain partners suppliers or distributors through an ERP system.

As seen from figure 3, if RFID is deployed throughout the supply chain, the central processing unit could have data about product status from all the segments of the supply chain, for example, data collected from manufacturer may be regarding the age of the items and the manufacturing lot size and data collected from retailer may be PoS data. The data collected need to be processed before using into enterprise applications as per the input requirements of the applications. For example, in our case we need age-wise profile of inventory. Then the optimal decision parameters obtained from these decision support systems can be communicated to the respective player of the supply chain, for example, the optimal ordering quantity decision to supplier or to manufacturer, demand distribution, sales pattern or consumer behaviour to retailer, based on which he can take further action regarding promotions etc. Our model as of now proposes a single-stage model for inventory management and pricing, which makes most sense in the VMI (vendor managed inventory) setting, where the manufacturer is responsible for the inventory levels at the retail end and can also perhaps influence the price offered at the retailing side.

A functional viewpoint of information flow in supply chain is given by Raghuram & Rangaraj (2003). An information system has various functions such as data capture, display and organization including identification of relevant data elements and collection. Other important functions are communication and processing at regular intervals. With RFID technology, the first two functions can be performed effectively. Figure 3 shows the role of RFID technology in such an architecture *vis-a-vis* information collection, storage and processing. Perishable inventory management thus can be seen as a potentially viable field of application for the RFID technology.

5.2 *Issues in implementation of RFID*

RFID implementation depends on the cost of change to the new technology as well as the benefits accruing from exploiting some of the possibilities that the technology brings. In principle, RFID technology provides up-to-the-minute information, which creates opportunities to do things efficiently. RFID technology identifies hundreds of tags per second and collects a lot of information. Each of these identification data and event-related data needs to be filtered prior to use in a business application. Various software applications need to be modified and the IT infrastructure may need to be extended to support RFID operations. A new generation of interfacing tools is emerging in this area. Some of the RFID technology implementation issues that need to be considered are listed below.

(1) *Cost*: Cost is a major factor which influences the decision to adopt RFID technology. Various costs involved in implementation of such technology are infrastructure cost, cost of training for personnel and operational cost. Cost of training is low as minimum or no human intervention is required. Operational cost depends upon cost of tag, process of attaching tag for identification and cost of operating RFID system. Out of these costs, cost of tags has a greater influence on the total cost of technology. Currently, passive tags are available at 15 cents per tag and these prices are diminishing with time; it is expected that cost per tag will decrease to about 1 cent by 2007.

(2) *Level of identification*: It is important to decide the level of identification, as it not only affects efficiency but also the operational cost. There can be any of the three levels of identification for RFID tagging, i.e., item level, pallet level or case level. As of now, for many practical level applications, it is pallet-level tagging or case level that is being considered. While this may have implications on warehouse management and upstream applications, full-fledged applications on the retail side may be fully meaningful only with item level tagging. The level of identification also depends on the constraints on cost or any other manufacturing constraints. For example, in case of the raw material that is going to be processed or where the physical shape of the object is going to be changed, item level tagging is not relevant.

(3) *Level of automation*: A company already having some level of automation for processing data will have an advantage; otherwise the initial cost of installation and training will be higher. For example, a company already having ERP systems can integrate the data from RFID at a lower cost.

(4) *Integration*: RFID technology generates an enormous amount of data. The success of RFID implementation depends on the effective use of these data. When these data are

generated for the first time, significant changes in the architecture of the existing systems are needed to use them. An important aspect of this is integration of the RFID system with other existing information systems.

(5) *Tangible benefits*: As discussed in previous sections, for perishable items, the total inventory-related costs and consequences of shortages can be minimized. In general, service levels are expected to improve for a given inventory investment. In any particular instance, some of these benefits can be estimated in tangible terms.

(6) *Intangible benefits*: Real-time data collection, improved service level, data transparency and reduced unaccounted assets are some of the intangible benefits that are difficult to quantify while implementing RFID technology. However, these are important considerations that need to be taken into account.

Apart from the issues mentioned above, there are issues like privacy of customers, as it may be possible to track the items after sale, and the emergence of RFID standards across industry segments, including technology solution providers (Hellstrom 2004).

6. Conclusion

The proposed model for inventory control of perishable products makes it possible to determine optimal timing for discount offers and also optimal order quantity. An approximation model is proposed, which produces results close to optimal, while reducing the complexity of the model.

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 offers, if the age of all available items is known, then decisions regarding quantity to be ordered and promotions 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. In order to successfully implement RFID technology, there is a need for development of measures and indicators which enable the inventory control system developer to be able to determine for a particular situation, (a) whether such development would be beneficial, and (b) when implemented, how the performance of the system compares to the performance without auto ID enhancements. 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.

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Appendix A. RFID technology

A typical RFID system consists of mainly three components.

(1) *RF reader*: An RFID system consists of a reading device called tag reader. This reader communicates with tags via radio frequency. Then the reader communicates this information to the RF unit. Readers are available in various sizes and different operating frequencies. Reading range of a typical reader is about 2700 m^2 of floor space.

(2) *RF tags*: A typical RFID tag consists of a microchip and an antenna. The information about the object is stored on the microchip, while the antenna is used to communicate with the reader. Tags are attached to the objects that need to be tracked or identified. Tags could be either active (with power source) or passive (without power source) according to the capability of communicating data.
(3) *RF unit*: The RF unit communicates with the individual tag reader via radio signals. It is connected to the host computer. It sends the information about the objects to the database of the host computer and the object status is updated.

Electronic product code (EPC):

EPC is a standard for immediate and accurate identification of objects. EPC refers to an electronic identification number for each individual object (Sarma *et al* 1999). This code is embedded on a memory chip in a tag that utilizes radio frequencies to connect the object to a network. In turn, the tags communicate their EPC codes to tag readers located in plants, warehouses, and stores.

The following features can be identified with RFID used for product identification (Sarma *et al* 1999)

(1) An RFID tag attached to a product with a microchip capable of storing (at least) an unique identification number and communicating this number via an RFID reader.
(2) RFID readers and data processing system capable of collecting signals from multiple tags at high speed (100s per second) and of preprocessing this data in order to eliminate duplications and misreads.
(3) One or more networked databases storing the information related to the product (basic product data, tracking history, processing instructions) whose entries are uniquely bound to the product identification number.

Appendix B.

Table B1. Sequence of decisions for the sample path of figure 3.

	Time period									
Inv. vector	1	2	3	4	5	6	7	8	9	10
When state can be promoted or not promoted, i.e., $a \in (n, p)$										
0,0,0,0	N-3	N-3	N-3	N-3	N-3	N-3	N-3	N-3	N-3	P-4
0,0,2,0	N-1	N-1	N-1	N-1	N-1	N-1	N-1	N-1	N-1	P-2
0,2,1,0	N-0	N-0	N-0	N-0	N-0	N-0	N-0	N-0	N-0	P-1
1,0,0,0	N-2	N-2	N-2	N-2	P-5	P-5	P-5	P-5	P-5	P-3
When state can only be promoted, i.e., $a \in (p)$										
0,2,1,0	P-3	P-3	P-3	P-3	P-3	P-3	P-3	P-3	P-3	P-1
0,0,2,0	P-4	P-4	P-4	P-4	P-4	P-4	P-4	P-4	P-4	P-2
0,0,3,0	P-3	P-3	P-3	P-3	P-3	P-3	P-3	P-3	P-3	P-1

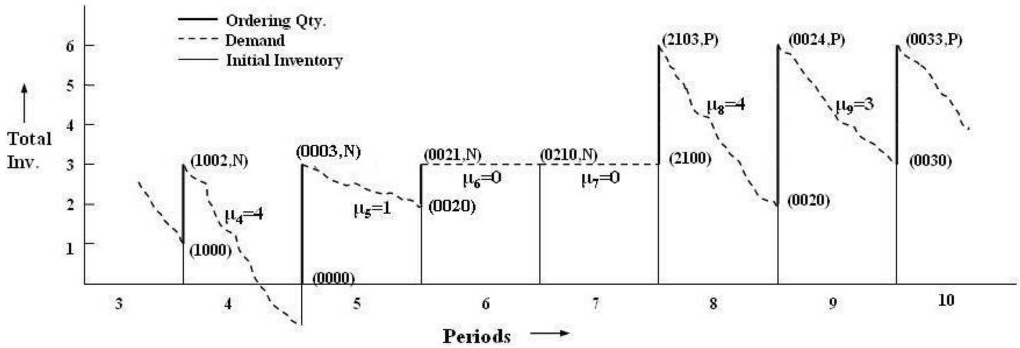

Figure B1. Sample path of total inventory

References

Abad P 2003 Optimal pricing and lot-sizing under conditions of perishability, finite production and partial backordering and lost sales. *Eur. J. Oper. Res.* 144: 677–685

Adachi Y, Nose T, Kuriyama S 1999 Optimal inventory control policy subject to different selling prices of perishable commodities. *Int. J. Product. Econ.* 60-61: 389–394

Anon 2005 WalMart Begins RFID Rollout. *RFID J.* available at http://www.rfidjournal.com/article/articleview/926/1/1/

Barker J, Mahadevan A 2004 Silent commerce: An overview of the technology and its commercial applications in the supply chain, available at, http://www.it.bond.edu.au/publications/04TR/04-01.pdf

Bertsekas D 1995 *Dynamic programming and optimal control*. (Belmont, MA: Athena Scientific) vols. 1 & 2

Chande A, Hemachandra N, Rangaraj N 2004 Fixed-life perishable inventory problem and approximation under price promotion. Technical Report, Industrial Engineering and Operations Research, Indian Institute of Technology Bombay, Mumbai

Chiu H 1995 An approximation to the continuous review inventory model with perishable items and lead times. *Eur. J. Oper. Res.* 87: 93–108

Feng Y, Gallego G 1995 Optimal starting times for end-of-season sales and optimal stopping times for promotional fares. *Manage. Sci.* 41: 1371–1391

Fries B 1975 Optimal ordering policy for perishable commodity with fixed-lifetime. *Oper. Res.* 23: 46–61

Gallego G, Van Ryzin G 1994 Optimal dynamic of inventorties with stochastic demand over finite horizons. *Manage. Sci.* 40: 999–1020

Goyal S, Giri B 2001 Recent trends in modelling of deteriorating inventory. *Eur. J. Oper. Res.* 134: 1–16

Hellstrom D 2004 Exploring the potential of using radio frequency identification technology in retail supply chain. Technical Report, Department of Design Sciences, Lund University, Sweden

Karkkainen M 2002 RFID in the grocery supply chain – a remedy for logistics problems or mere hype, available at http://www.ecracademics.org/partnership/pdf/award/KaerkkaeinenECRStudentAward2002-Bronze.pdf

Konda C, Dave N, Hemachandra N, Rangaraj N 2003 Timing of discount offers for perishable inventories. In *Proceeding of Sixth Asia Pacific Operations Research Society* (eds) M R Rao, M C Puri (New Delhi: Allied Publishers)

Lilien G, Kotler P, Moorthy S 1999 *Marketing models* (New Delhi: Prentice Hall of India)

Luo W 1997 An integrated inventory system for perishable goods with backordering. *Comput. Ind. Eng.* 34: 685–693

Mandal P, Gunasekaran A 2002 Application of SAP R/3 in on-line inventory control. *Int. J. Product. Econ.* 75: 47–55

McFarlane D, Sarma S, Chirn J, Wong C, Ashton K 2003 Auto ID system and intelligent manufacturing control. *Eng. Appl. Artif. Intell.* 16: 365–376

Moran H, McFarlane D 2003 Auto-ID use case: Improving differential item pricing in a retail company–Impact on existing procedures and information systems. Auto-Id Center, available at http://www.autoidlabs.org/whitepapers/CAM-AUTOID-WH020.pdf

Nahmias S 1982 Approximation techniques for several stochastic inventory models. *Comput. Oper. Res.* 8: 141–158

Nahmias S 1974 Optimal ordering policies for perishable inventory – II. *Oper. Res.* 23: 735–749

Nahmias S 1977 Higher order approximations for the perishable inventory problem. *Oper. Res.* 25: 630–640

Narahari Y, Raju C V L, Ravikumar K, Shah S 2005 Dynamic pricing models for electronic business. *Sādhanā* 30:

Puterman M 1994 *Markov decision processes* (New York: John Wiley & Sons)

Raghuram G, Rangaraj N 2003 *Logistics and supply chain management: Cases and concepts* (New Delhi: Macmillan India)

Sarma S, David L, Ashton K 1999 The networked physical world. Auto ID Center Technical Report, available at http://www.autoidlabs.com/whitepapers/MIT-AUTOID-WH-001.pdf

Weiss H 1980 Optimal ordering policies for continuous review perishable inventory models. *Manage. Sci.* 42: 1097–1104

Yao A, Carlson J 1999 Impact of real-time data communication on inventory management. *Int. J. Product. Eco.* 59: 213–219