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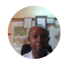

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Optimal Ordering Policies for Supermarkets under Static Pricing and Stochastic Demand: A Case Study of Milk Powder Product

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Abstract
Demand uncertainty affects a significant portion of sales revenue in supermarkets. In this paper, we develop a new approach to formulate and optimize the single-item, finite horizon, periodic review revenue problem of milk powder product under stochastic demand. A special case of our model is where sales price and scheduled inventory replenishment periods are uniformly fixed at all supermarkets. Adopting a Markov decision process approach, the states of a Markov chain represent possible states of demand for milk powder product. The decision of whether or not to order additional units is made using dynamic programming over a finite period planning horizon. Numerical results demonstrate the existence of an optimal state-dependent ordering policy and the corresponding sales revenue of milk powder product in supermarkets.

Key words: Optimization, ordering policies, static pricing, stochastic demand

1 Introduction
Supermarkets continually face the challenge of optimizing sales revenue of items in a stochastic demand environment. One major problem is to determine the most desirable period during which to order additional units of the item in question in order to maximize sales revenue given a periodic review inventory system when demand is uncertain. In this paper, an inventory system is considered whose goal is to optimize the sales revenue associated with ordering and holding inventory of milk powder product. At the beginning of each period, a major decision has to be made, namely whether to order additional units of the item size in stock or postpone ordering and utilize the available units in inventory. Customers pay for the same price per unit in supermarkets and scheduled inventory replenishments can be made on time. Given this information, the supermarkets may decide for customer orders whether to satisfy them from stock or make additional orders.

2 Literature Reviews
Federgrunen & Heching [1] addressed combined pricing and inventory control under demand uncertainty. In this article, demands in consecutive periods are independent, but their distributions depend on the item's price in accordance with general stochastic demand functions. The price charged in any given period can be specified dynamically as a function of the state of the system. The model has restrictions to a dynamic pricing setting. In a similar context, joint optimization on pricing and inventory control with stochastic demand was proposed in [2].The paper provides an analytical method for obtaining optimal decisions jointly on pricing, promotion and inventory control. Demand is influenced by price promotion and the objective is to maximize the total profit. The optimal solution is characterized and a solution is provided for coordinating promotion pricing and inventory replenishment. The model has profound insights especially in terms of inventory/pricing policy and stochastic demand. However, dynamic adjustment of prices is considered in this model and its impact on sales revenue is not explicit. In related literature, bundle pricing of inventories with stochastic demand is examined in [3]. A retailer is considered, selling a fixed inventory of two perishable products over a finite horizon. The optimal product and bundle prices that maximize expected revenue are determined and largely depend on the parameters of the demand process and the initial inventory levels. The model is extended to allow for price changes during the selling season. In this model price changes are allowed and revenue optimization is not a salient issue. In the article presented in [4], the value of coordinating static pricing and revenue management availability decisions under price sensitive demand uncertainty are investigated. The hierarchical revenue management process can yield significant revenue benefits and thereby achieve most of the potential of a fully coordinated process. The inventory ordering policies are however excluded in such a setting.
The paper is organized as follows. After describing the mathematical model in §3, consideration is given to the process of estimating the model parameters. The model is solved in §4 and applied to a special case study in §5.Some final remarks lastly follow in §6.

3 Model Formulations
We consider a designated number of supermarkets whose demand of milk powder product during each time period over a fixed planning horizon is classified as either *favorable*(denoted by state F) or *unfavorable* (denoted by state U) and the demand of any such period is assumed to depend on the demand of the preceding period. The transition probabilities over the planning horizon from one demand state to another may be described by means of a Markov chain. Suppose one is interested in determining an optimal course of action, namely to order additional units (a decision denoted by K=1) or not to order additional units (a decision denoted by K=0) during each time period over the planning horizon, where K is a binary decision variable. Optimality is defined such that the maximum expected sales revenue is accumulated at the end of N consecutive time periods spanning the planning horizon under consideration. In this paper, a three supermarket (S =3) and two-period (N=2) planning horizon is considered.

3.1 Assumptions and notation

Varying demand is modeled by means of a Markov chain with *state transition matrix* $Q^K(S)$ where the entry $Q^K_{ij}(S)$ in row i and column j of the transition matrix denotes the probability of a transition in demand from state i$\epsilon$$\{F, U\}$ to state j$\epsilon$$\{U, F\}$ in supermarket S $\epsilon\{1,2,3\}$under a given ordering policy K$\epsilon\{0,1\}$ over one week period. The number of customers observed in the system and the number of units demanded during such a transition is captured by the *customer matrix* $N^K(S)$ and *demand matrix* $D^K(S)$ respectively. Furthermore, denote the number of units in inventory and the sales revenue during such a transition by the *inventory matrix* $I^K(S)$ and the *revenue matrix* $R^K(S)$ respectively. Also, denote the *expected future sales revenue*, the already *accumulated sales revenue* at the end of period *n* when the demand is in state i$\epsilon$$\{F, U\}$for a given ordering policy K$\epsilon\{0,1\}$ by respectively $e^K(S)$ and $a^K_i(S,n)$ and let $e^K(S) = [e^K_F(S), e^K_U(S)]^T$ and $a^K(S,n) = [a^K_F(S,n), a^K_U(S,n)]^T$ where "T" denotes matrix transposition.

3.2 Finite period dynamic programming formulation

Recalling that the demand can either be in state *F* or in state *U*, the problem of finding the optimal sales revenue may be expressed as a finite period dynamic programming model.

Let $R_n(i, S)$ denote the optimal expected sales revenue of milk powder in supermarket S accumulated during the periods *n,n+1,…....,N* given that the state of the system at the beginning of period *n* is i$\epsilon\{F,U\}$.The recursive equation relating R_n and R_{n+1} is

$$R_n(i, S) = \max_K\{(Q^K_{iF}(S)(R^K_{iF}(S) + R_{n+1}(F, S), R^K_{iU}(S) + R_{n+1}(U, S))\} \qquad (1)$$

$$i \in \{F,U\} \quad n=1,2\ldots\ldots N \quad S = 1, 2, 3$$

together with the final conditions

$R_{N+1}(F, S) = R_{N+1}(U, S) = 0$.

This recursive relationship may be justified by noting that the cumulative sales revenue

$R^K_{ij}(S) + R_{n+1}(j, S)$ resulting from reaching state j$\epsilon\{F,U\}$ at the start of period *n*+1 from state i$\epsilon\{F,U\}$ at the start of period *n* occurs with probability $Q^K_{ij}(S)$.

The dynamic programming recursive equations become:

$$R_n(i, S) = \max_K\{e^K_i(S) + Q^K_{iF}(S)R_{n+1}(F, S) + Q^K_{iU}(S)R_{n+1}(U,S)\}$$

$$i\epsilon\{F, U\} \quad n = 1, 2\ldots\ldots\ldots N \quad S = \{1, 2, 3\} \quad K\epsilon\{0,1\} \qquad (2)$$

$$R_N(i, S) = \max_K\{e^K_i(S)\} \qquad (3)$$

result, where (3) represents the Markov chain stable state.

3.2.1 Computing $Q^K(S)$ and $R^K(S)$

The demand transition probability from state i$\epsilon\{F, U\}$ to state j$\epsilon\{F, U\}$,given ordering policy K$\epsilon\{0,1\}$ may be taken as the number of customers observed in supermarket S with demand initially in state i and later with demand changing to state j, divided by the sum of customers over all states. That is,

$$Q^K_{ij}(S) = \frac{N^K_{ij}(S)}{[N^K_{if}(S) + N^K_{iU}(S)]}$$

$$i\epsilon\{F, U\}, \quad S = \{1, 2, 3\}, \quad K\epsilon\{0,1\} \qquad (4)$$

When demand outweighs on-hand inventory or vice-versa, the sales revenue matrix $R^K(S)$ may be computed by means of the relation

$R^K(S) = p[D^K(S) - I^K(S)] + p\, I^K(S) = p\, D^K(S)$

where *p* denotes the unit sales price

Therefore,

$$R^K_{ij}(S) = p[D^K_{ij}(S) – I^K_{ij}(S)] + p\, I^K_{ij}(S) = p\, D^K_{ij}(S) \qquad (5)$$

for all i,j$\epsilon\{F, U\}$,K$\epsilon\{0,1\}$ and S $\epsilon\{1,2,3\}$

A justification for expression (5) is that $D^K_{ij}(S) – I^K_{ij}(S)$ units must be replenished in order to meet the excess demand. Otherwise ordering is cancelled when demand is less than or equal to the on-hand inventory.

4 Optimization

The optimal sales revenue and ordering policy are found in this section for each time period separately.

4.1 Optimization during period 1

When demand is Favorable (ie. in state *F*), the optimal ordering policy during period 1 is

$$K = \begin{cases} 1 & \text{if } e^1_F(S) > e^0_F(S) \\ 0 & \text{if } e^1_F(S) \leq e^0_F(S) \end{cases}$$

The associated sales revenue is then

$$R_1(F,S) = \begin{cases} e^1_F(S) & \text{if } K = 1 \\ e^0_F(S) & \text{if } K = 0 \end{cases}$$

Similarly, when demand is Unfavorable (ie. in state *U*), the ordering policy during period 1 is

$$K = \begin{cases} 1 & \text{if } e^1_U(S) > e^0_U(S) \\ 0 & \text{if } e^1_U(S) \leq e^0_U(S) \end{cases}$$

In this case, the associated sales revenue is

$$R_1(U,S) = \begin{cases} e^1_U(S) & \text{if } K = 1 \\ e^0_U(S) & \text{if } K = 0 \end{cases}$$

Using (2),(3) and recalling that $a^K_i(S,2)$ denotes the already accumulated sales revenue at the end of period 1 as a result of decisions made during that period, it follows that

$$a^K_i(S,2) = e^K_i(S) + Q^K_{iF}(S) \max \{e^1_F(S), e^0_F(S)\} + Q^K_{iU}(S) \max \{e^1_U(S), e^0_U(S)\}$$
$$= e^K_i(S) + Q^K_{iF}(S)\, R_1(F, S) + Q^K_{iU}(S)\, R_1(U, S)$$

4.2Optimization during period 2

Using the dynamic programming recursive equation(1), and recalling that $a^K_i(S)$ denotes the already accumulated sales revenue at the end of period 1 as a result of decisions made during that period, when demand is favorable (ie. in state *F*),the optimal ordering policy during period 2 is

$$K = \begin{cases} 1 & \text{if } a^1_F(S) > a^0_F(S) \\ 0 & \text{if } a^1_F(S) \le a^0_F(S) \end{cases}$$

While the associated sales revenue is

$$R_2(F, S) = \begin{cases} a^1_F(S) & \text{if } K = 1 \\ a^0_F(S) & \text{if } K = 0 \end{cases}$$

Similarly, when demand is unfavorable (ie. in state *U*),the optimal ordering policy during period 2 is

$$K = \begin{cases} 1 & \text{if } a^1_U(S) > a^0_U(S) \\ 0 & \text{if } a^1_U(S) \le a^0_U(S) \end{cases}$$

In this case, the associated sales revenue is

$$R_2(U,S) = \begin{cases} a^1_U(S) & \text{if } K = 1 \\ a^0_U(S) & \text{if } K = 0 \end{cases}$$

5 Implementation

5.1 Case Description

In order to demonstrate use of the model in §3-4,a real case application from *Shoprite supermarket* ,*Game supermarket* and *Uchumi supermarket* in Uganda is presented in this section. The supermarkets want to maximize sales revenue irrespective of the state of demand: Favorable (state *F*) of unfavorable(state *U*) and hence seek decision support in terms of an optimal ordering policy and the associated sales revenue of milk powder product over the next two-week period.

5.2 Data collection

Samples of customers for milk powder were taken at each respective supermarket. Past data revealed the following demand pattern and inventory levels of milk powder product over the first week of the month when demand was Favorable (*F*) or Unfavorable (*U*).The number of customers and demand for milk powder at the supermarkets under the respective state transitions and ordering policies are presented below:

Shoprite supermarket :(S = 1)

$$N^1(1) = \begin{bmatrix} N^1_{FF}(1) & N^1_{FU}(1) \\ N^1_{UF}(1) & N^1_{UU}(1) \end{bmatrix}$$

$$N^1(1) = \begin{bmatrix} 91 & 71 \\ 64 & 13 \end{bmatrix}$$

$$D^1(1) = \begin{bmatrix} D^1_{FF}(1) & D^1_{FU}(1) \\ D^1_{UF}(1) & D^1_{UU}(1) \end{bmatrix}$$

$$D^1(1) = \begin{bmatrix} 156 & 115 \\ 107 & 11 \end{bmatrix}$$

$$N^0(1) = \begin{bmatrix} N^0_{FF}(1) & N^0_{FU}(1) \\ N^0_{UF}(1) & N^0_{UU}(1) \end{bmatrix}$$

$$N^0(1) = \begin{bmatrix} 82 & 50 \\ 56 & 25 \end{bmatrix}$$

$$D^0(1) = \begin{bmatrix} D^0_{FF}(1) & D^0_{FU}(1) \\ D^0_{UF}(1) & D^0_{UU}(1) \end{bmatrix}$$

$$D^0(1) = \begin{bmatrix} 123 & 78 \\ 78 & 15 \end{bmatrix}$$

Game supermarket :(S = 2)

$$N^1(2) = \begin{bmatrix} N^1_{FF}(2) & N^1_{FU}(2) \\ N^1_{UF}(2) & N^1_{UU}(2) \end{bmatrix}$$

$$N^1(2) = \begin{bmatrix} 48 & 55 \\ 59 & 13 \end{bmatrix}$$

$$D^1(2) = \begin{bmatrix} D^1_{FF}(2) & D^1_{FU}(2) \\ D^1_{UF}(2) & D^1_{UU}(2) \end{bmatrix}$$

$$D^1(2) = \begin{bmatrix} 93 & 60 \\ 59 & 11 \end{bmatrix}$$

$$N^0(2) = \begin{bmatrix} N^0_{FF}(2) & N^0_{FU}(2) \\ N^0_{UF}(2) & N^0_{UU}(2) \end{bmatrix}$$

$$N^0(2) = \begin{bmatrix} 54 & 46 \\ 45 & 11 \end{bmatrix}$$

$$D^0(2) = \begin{bmatrix} D^0_{FF}(2) & D^0_{FU}(2) \\ D^0_{UF}(2) & D^0_{UU}(2) \end{bmatrix}$$

$$D^0(2) = \begin{bmatrix} 72 & 77 \\ 75 & 11 \end{bmatrix}$$

Uchumi supermarket :(S=3)

$$N^1(3) = \begin{bmatrix} N^1_{FF}(3) & N^1_{FU}(3) \\ N^1_{UF}(3) & N^1_{UU}(3) \end{bmatrix}$$

$$N^1(3) = \begin{bmatrix} 57 & 62 \\ 62 & 9 \end{bmatrix}$$

$$D^1(3) = \begin{bmatrix} D^1_{FF}(3) & D1_{FU}(3) \\ D^1_{UF}(3) & D1_{UU}(3) \end{bmatrix}$$

$$D^1(3) = \begin{bmatrix} 82 & 93 \\ 84 & 9 \end{bmatrix}$$

$$N^0(3) = \begin{bmatrix} N^0_{FF}(3) & N^0_{FU}(3) \\ N^0_{UF}(3) & N^0_{UU}(3) \end{bmatrix}$$

$$N^0(3) = \begin{bmatrix} 36 & 53 \\ 56 & 9 \end{bmatrix}$$

$$D^0(3) = \begin{bmatrix} D^0_{FF}(3) & D^0_{FU}(3) \\ D^0_{UF}(3) & D^0_{UU}(3) \end{bmatrix}$$

$$D^0(3) = \begin{bmatrix} 51 & 70 \\ 72 & 10 \end{bmatrix}$$

The price of Milk powder (400 gms) is 6000 UGX (0.006M.UGX) at each respective supermarket.

5.3 Solution Procedure for the case of Shoprite, Game and Uchumi supermarkets

Using (4) and (5), the state transition matrices and sales revenue matrices (in million UGX) at each respective supermarket in week 1 are as follows:

When additional units are ordered (K=1),

$$Q^1(1) = \begin{bmatrix} 0.5697 & 0.4303 \\ 0.8312 & 0.1688 \end{bmatrix}$$

$$Q^1(2) = \begin{bmatrix} 0.4660 & 0.5340 \\ 0.8429 & 0.1571 \end{bmatrix}$$

$$Q^1(3) = \begin{bmatrix} 0.4790 & 0.5210 \\ 0.8732 & 0.1268 \end{bmatrix}$$

$$R^1(1) = \begin{bmatrix} 0.57 & 0.56 \\ 0.56 & 0.56 \end{bmatrix}$$

$$R^1(2) = \begin{bmatrix} 0.56 & 0.36 \\ 0.35 & 0.07 \end{bmatrix}$$

$$R^1(3) = \begin{bmatrix} 0.49 & 0.56 \\ 0.50 & 0.05 \end{bmatrix}$$

When additional units are not ordered (K=0),

$$Q^0(1) = \begin{bmatrix} 0.6212 & 0.3722 \\ 0.6914 & 0.3086 \end{bmatrix}$$

$$Q^0(2) = \begin{bmatrix} 0.5400 & 0.4600 \\ 0.8036 & 0.1964 \end{bmatrix}$$

$$Q^0(3) = \begin{bmatrix} 0.404 & 0.596 \\ 0.862 & 0.138 \end{bmatrix}$$

$$R^0(1) = \begin{bmatrix} 0.74 & 0.47 \\ 0.47 & 0.09 \end{bmatrix}$$

$$R^0(2) = \begin{bmatrix} 0.43 & 0.46 \\ 0.45 & 0.07 \end{bmatrix}$$

$$R^0(3) = \begin{bmatrix} 0.32 & 0.42 \\ 0.43 & 0.06 \end{bmatrix}$$

When additional units are ordered (K = 1), the matrices Q^1 (1), R^1(1) , Q^1 (2) , R^1(2) , Q^1 (3) and R^1(3) yield the sales revenue(in million UGX)

$e^1_F(1) = (0.5697)(0.57) + (0.4303)(0.56) = 0.566$
$e^1_U(1) = (0.8312)(0.56) + (0.4688)(0.56) = 0.728$
$e^1_F(2) = (0.4660)(0.56) + (0.5340)(0.36) = 0.453$
$e^1_U(2) = (0.8429)(0.35) + (0.1571)(0.07) = 0.306$
$e^1_F(3) = (0.4790)(0.49) + (0.5210)(0.56) = 0.526$
$e^1_U(3) = (0.8732)(0.50) + (0.1268)(0.05) = 0.443$

However, when additional units are *not* ordered (K= 0), the matrices Q^0 (1), R^0(1) , Q^0 (2) , R^0(2) , Q^0 (3) and R^0(3) yield the sales revenue(in million UGX)

$e^{0}_{F}(1) = (0.6212)(0.74) + (0.3718)(0.47) = 0.634$
$e^{0}_{U}(1) = (0.6914)(0.47) + (0.3086)(0.09) = 0.353$
$e^{0}_{F}(2) = (0.5400)(0.43) + (0.4600)(0.46) = 0.444$
$e^{0}_{U}(2) = (0.8036)(0.45) + (0.4964)(0.07) = 0.396$
$e^{0}_{F}(3) = (0.4040)(0.32) + (0.5960)(0.42) = 0.380$
$e^{0}_{U}(3) = (0.8620)(0.43) + (0.1380)(0.06) = 0.379$

The results are summarized in Tables 1 and 2 below:

Table 1
Values of K and $e^{K}_{i}(S)$ for 400gms milk powder during week 1(n=1)

Supermarket (S)	**K = 1**	**K = 0**
Shoprite (1)		
$e^{K}_{F}(1)$	0.566	0.634
$e^{K}_{U}(1)$	0.728	0.353
Game (2)		
$e^{K}_{F}(2)$	0.453	0.444
$e^{K}_{U}(2)$	0.306	0.396
Uchumi (3)		
$e^{K}_{F}(3)$	0.526	0.380
$e^{K}_{U}(3)$	0.443	0.379

The cumulative sales revenue $a^{K}_{i}(S,n)$ are computed using (1) for week 2 and results are summarized in Table 2 below:

Table 2
Values of K and $a^{K}_{i}(S,n)$ for 400gms full cream milk powder during week 2(n=2)

Supermarket (S)	**K = 1**	**K = 0**
Shoprite (1)		
$a^{K}_{F}(1,2)$	1.240	1.299
$a^{K}_{U}(1,2)$	1.378	1.016
Game (2)		
$a^{K}_{F}(2,2)$	0.876	0.871
$a^{K}_{U}(2,2)$	0.750	0.838
Uchumi (3)		
$a^{K}_{F}(3,2)$	1.009	0.857
$a^{K}_{U}(3,2)$	0.958	0.894

5.4 The Optimal ordering policy and Sales revenue

Week1

Shoprite supermarket

Since 0.634 > 0.566, it follows that K=0 is an optimal ordering policy for week 1 with associated sales revenue of 0.634 million UGX when demand is favorable. Since 0.728 > 0.353, it follows that K=1 is an optimal ordering policy for week 1 with associated sales revenue of 0.728 million UGX if demand is unfavorable.

Game supermarket

Since 0.453 > 0.444, it follows that K=1 is an optimal ordering policy for week 1 with associated sales revenue of 0.453 million UGX when demand is favorable. Since 0.396 > 0.306, it follows that K=0 is an optimal ordering policy for week 1 with associated sales revenue of 0.396 million UGX if demand is unfavorable.

Uchumi supermarket

Since 0.526 > 0.380, it follows that K=1 is an optimal ordering policy for week 1 with associated sales revenue of 0.526 million UGX when demand is favorable. Since 0.443 > 0.379, it follows that K=1 is an optimal ordering policy for week 1 with associated sales revenue of 0.443 million UGX if demand is unfavorable.

Week 2

Shoprite supermarket

Since 1.299 > 1.240 it follows that K=0 is an optimal ordering policy for week 2 with associated accumulated sales revenue of 1.299 million UGX when demand is favorable. Since 1.378 > 1.016, it follows that K=1 is an optimal ordering policy for week 2 with associated accumulated sales revenue of 1.378 million UGX if demand is unfavorable.

Game supermarket

Since 0.876 > 0.871, it follows that K=1 is an optimal ordering policy for week 2 with associated accumulated sales revenue of 0.876 million UGX when demand is favorable. Since 0.838 > 0.750, it follows that K=0 is an optimal ordering policy for week 2 with associated accumulated sales revenue of 0.838 million UGX if demand is unfavorable.

Uchumi supermarket

Since 1.009 > 0.857, it follows that K=1 is an optimal ordering policy for week 2 with associated accumulated sales revenue of 1.009 million UGX when demand is favorable. Since 0.958 > 0.894, it follows that K=1 is an optimal ordering policy for week 2 with associated accumulated sales revenue of 0.958 million UGX if demand is unfavorable.

6 Conclusion

An optimization model with static pricing and stochastic demand was presented in this paper. The model determines an optimal ordering policy and sales revenue of a single-item, finite horizon, periodic review inventory problem with stochastic demand. The decision of whether or not to order additional stock units is modeled as a multi-period decision problem using dynamic programming over a finite planning horizon. The working of the model was demonstrated by means of a real case study. It would however be worthwhile to extend the research and examine the behavior of ordering policies under non stationary demand conditions and dynamic pricing. Finally, special interest is thought in further extending our model by optimizing ordering policies and the corresponding sales revenue using Continuous Time Markov Chains (CTMC).

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