Chapter VI

Multi-Commodity Inventory Problem
Perishable due to Decay and Disaster

6.1 INTRODUCTION

In this chapter an attempt is made to study a continuous review multi-commodity perishable inventory system. The \( n \) commodities, \( C_1, C_2, \ldots, C_n \), are diminished from the inventory due to demands, decay and disaster. The maximum inventory level and the re-ordering point of commodity \( C_k \) are \( S_k \) and \( s_k \) respectively, \((k = 1, 2, \ldots, n)\). Shortages are not allowed and the lead time is assumed to be zero. Fresh orders are placed whenever the inventory level of at least one of the commodities falls to or below the re-ordering point for the first time after the previous replenishment. Demands for commodity \( C_k \) are assumed to follow Poisson process with rate \( \lambda_k \). The lifetime times of commodity \( C_k \) follow exponential distribution with parameter \( \omega_k \). The distribution of the times between the disasters is exponential with mean \( 1/\mu \). Each unit of commodity \( C_k \) survives a disaster with probability \( p_k \) and is destroyed completely with probability \( 1-p_k \) independently of others. The damaged items are removed from the inventory instantaneously.

\[ s^* = s_0 + 1 + s_{n-1} M_n + s_{n-2} M_{n-1} M_n + \ldots + s_1 M_2 \ldots M_n \]

\[ S_k^* = s_k + 1 + s_{n-1} M_n + s_{n-2} M_{n-1} M_n + \ldots + (s_1 - 1) M_2 \ldots M_n \]

*The results of this chapter have been presented in the International Conference on Stochastic Processes held at Cochin (1996).
This chapter generalizes the results of chapter II to multi-commodity case. The objectives of this chapter are to find transient and stationary probabilities of the inventory states and the optimum value of the 2n-tuple, \((s_1, s_2, ..., s_n, S_1, S_2, ..., S_n)\) at steady state. The scheme of presentation of the chapter is as follows: In section 6.2 the notations used are explained while in section 6.3 the transient solution is arrived at. The stationary probabilities and the expected length of the replenishment periods are derived in section 6.4. Section 6.5 discusses optimization where as section 6.6 illustrates the model with numerical examples.

6.2 NOTATIONS

\(S_k\) : Maximum inventory level of commodity \(C_k (k = 1, 2, ..., n)\)

\(s_k\) : Re-ordering level of commodity \(C_k (k = 1, 2, ..., n)\)

\(M_k\) : The inventory level of commodity \(C_k (k = 1, 2, ..., n)\) at any time \(t \geq 0\).

\(M\) : \(M_1 \times M_2 \times ... \times M_n\)

\(q_k\) : \(1 - p_k\)

\(R^+\) : The set of non-negative real numbers

\(\mathbb{N}^0\) : The set of non-negative integers

\(E_k\) : \(\{s_k + 1, s_k + 2, ..., S_k\}\)

\(E_{10}\) : \(\{s_1, s_1 + 1, ..., S_1\}\)

\(E\) : \(E_1 \times E_2 \times ... \times E_n\)

\(E_0\) : \(E_1 \times E_2 \times ... \times E_n\)

\(i^*\) : \(i_n + (i_{n-1} - 1)M_n + (i_{n-2} - 1)M_{n-1}M_n + ... + (i_1 - 1)M_2M_3 ... M_n\)

\(s^*\) : \(s_n + 1 + s_{n-1}M_n + s_{n-2}M_{n-1}M_n + ... + s_1M_2 ... M_n\)

\(s_1^*\) : \(s_n + 1 + s_{n-1}M_n + s_{n-2}M_{n-1}M_n + ... + (s_1 - 1)M_2 ... M_n\)

\(S^*\) : \(S_n + (S_{n-1} - 1)M_n + (S_{n-2} - 1)M_{n-1}M_n + ... + (S_1 - 1)M_2 ... M_n\)
E*: (s*, s*+1, ..........., S*)
\[ \alpha : (0, 0, ......., 1); \text{ M components} \]
\[ e: (1, 1, ......., 1)^T; \text{ M components} \]
\[ A: (a_{i1}i_2....i_n)_{M \times M}, \text{ where } a_{i1}i_2....i_n \text{'s are given by (6.4)} \]
\[ D_{s*}: \text{The determinant of the submatrix obtained from } A \text{ by deleting} \]
the first i*-s*+1 rows, the last and first i*-s* columns;
\[ i* \in E*-\{S*\} \]
\[ D_{s*^*} : 1 \]
\[ \delta(i, j) : 1 \text{ if } i = j; \ 0 \text{ otherwise} \]

6.3. ANALYSIS OF THE INVENTORY STATES

Let \( X_k(t) \) denote the inventory level of commodity \( C_k \) (k = 1, 2, ...., n) at any time \( t \geq 0 \). If \( X(t) = \{X_1(t), X_2(t), ......., X_n(t)\} \), then \( \{X(t), t \in \mathbb{R}^+\} \) is a continuous time Markov chain with state space \( E \). We assume that the initial probability vector of this chain is \( \alpha \).

Let the transition probability matrix of the Markov chain \( \{X(t)\} \) be
\[ P(t) = [P_{i_1j_1...j_n}]_{M \times M} \]
where
\[ P_{i_1j_1...j_n}(t) = \Pr\{X_1(t) = j_1, ..., X_n(t) = j_n / X_1(0) = i_1, ..., X_n(0) = i_n\} \]
(6.1)
\[ i_k, j_k \in E_k; \ k = 1, 2, ..., n \]

Theorem 6.1

The transition probability matrix \( P(t) \) is uniquely determined by
\[ P(t) = \exp(\mathbf{B}t) = I + \sum_{m=1}^{\infty} \frac{\mathbf{B}^m}{m!} t^m \]  \hspace{1cm} (6.2)

where the matrix \( \mathbf{B} = \mathbf{A} + \mathbf{G} \), in which \( \mathbf{A} \) and \( \mathbf{G} \) are defined as follows:

\[ \mathbf{A} = \left[ a_{i_1i_2...i_n \ j_1j_2...j_n} \right]_{M \times M} \quad \text{and} \quad \mathbf{G} = \left[ g_{i_1i_2...i_n \ j_1j_2...j_n} \right]_{M \times M} \]  \hspace{1cm} (6.3)

with

\[ a_{i_1i_2...i_n \ j_1j_2...j_n} = \begin{cases} \mu + \sum_{k=1}^{n} (\lambda_k + i_k \omega_k) & \text{if } i_k = j_k \quad k = 1, 2, ..., n \\ \mu p_1^{i_1} p_2^{i_2} ... p_k^{i_k} & \text{if } i_k = j_k \quad k = 1, 2, ..., n \\ \left( \lambda_k + i_k \omega_k \right) + \mu \prod_{l=1}^{k} p_l^{i_l} q_l^{i_l-j_l} \prod_{l=1}^{n} p_l^{i_l} & \text{if } i_k = j_k + 1, i_l = j_l (l = 1, 2, ..., n, l \neq k) \end{cases} \]  \hspace{1cm} (6.4)

\[ g_{i_1i_2...i_n \ j_1j_2...j_n} = \begin{cases} \sum_{k=1}^{n} \delta(s_k + 1, i_k) [\lambda_k + (s_k + 1) \omega_k] + \mu (1 - A_{i_1} A_{i_2} ... A_{i_n}) & \text{if } j_k = S_k \\ 0 & \text{otherwise} \end{cases} \]  \hspace{1cm} (6.5)

Proof:

For a fixed \( i_0 = (i_1, i_2, ..., i_n) \) the difference-differential equations satisfied by the transition probabilities are:
From equations (6.3) - (6.7) we can easily see that the Kolmogorov equations,

$$P'(t) = P(t)B$$  

with the initial condition,

$$P(0) = I$$

are satisfied by $P(t)$. The solution of (6.8) with (6.9) is (6.2). The finiteness of $B$ guarantees the convergence of the series in (6.2) and the solution obtained is unique. Hence the theorem.
6.4. STEADY STATE PROBABILITIES AND REPLISHMENT PERIODS

Since the transition from any state \((i_1, i_2, \ldots, i_n)\) to any state \((j_1, j_2, \ldots, j_n)\) in \(E\) is possible with positive probability, the Markov chain \(\{X(t), t \geq 0\}\) is irreducible. Therefore

\[
\lim_{t \to \infty} P_{i_1j_1\ldots j_n}(t) = \pi_{i_1j_1\ldots j_n} (j_1, j_2, \ldots, j_n) \in E
\]

exist. \(\pi_{i_1j_1\ldots j_n}\)'s are obtained by solving

\[
\Pi B = 0 \quad \text{and} \quad \Pi e = 1
\]

simultaneously. To solve (8) we define a function \(f\) from \(E\) to \(E^*\) as

\[
f((i_1, i_2, \ldots, i_n)) = i^* = i_n + (i_{n-1} - 1)M_n + (i_{n-2} - 1)M_{n-1}M_n + \ldots
\]

\[+ (i_1 - 1)M_2M_3 \ldots M_n; (i_1, i_2, \ldots, i_n) \in E; \quad i^* \in E^* (6.12)
\]

Since \(f\) is one-one and onto, henceforth \((i_1, i_2, \ldots, i_n)\) will be represented by \(i^*\).

**Theorem 6.2**

The steady state probabilities of the inventory states are given by,

\[
\pi_{i_1j_1\ldots j_n} = S^*_i \frac{D_{i^*}}{D^*_i}; \quad i^* \in E^*
\]

\[
F(s^*, s^*) \prod_{k = i^*} (-a_{k^*, k^*})
\]

where \(F(s^*, s^*) = \sum_{i = s^*} S^*_i \frac{D_{i^*}}{D^*_i}\) (6.14)

Proof:

Let \(D_{i^*}\) be the determinant of the submatrix obtained from A by deleting the first \(i^* - s^* + 1\) rows, the last and first \(i^* - s^*\) columns, \(i^* \in E^* - \{S^*\}\), and \(D_{S^*} = 1\). With these notations we can see that the solution of (6.11) is
\[ \pi_{i_1 i_2 \ldots i_n} = \pi_i = \frac{D_i \pi_i^*}{\prod_{k=1}^{i-1} (-a_{i_k}, k^*)} \quad i^* \in E^* \setminus \{S^*\} \quad (6.15) \]

and

\[ \pi_{S_1 S_2 \ldots S_n} = \pi_{S^*} = \frac{1}{-a_S S^* F(s^*, S^*)} \quad (6.16) \]

Substituting (6.16) in (6.15) we get (6.13). Hence the theorem.

Let \( T_0 = 0 < T_1 < T_2 < \ldots \) be the epochs when the orders are placed. This occurs whenever the inventory level of one of the commodities \( C_k \) falls to \( s_k \) or below it for the first time after the previous replenishment (\( k = 1, 2, \ldots, n \)). Since lead time is assumed to be zero, the stock level is immediately brought to \( (S_1, S_2, \ldots, S_n) \). Thus clearly \( \{T_m, m \in \mathbb{N}^0\} \) is a renewal process.

**Theorem 6.3**

If \( E(T) \) represents the expected time between two successive re-orders, then

\[ E(T) = F(s^*, S^*) = \frac{1}{-a S S^* \pi_{S^*}} \quad (6.17) \]

Proof:

By a similar argument as in section 4 of chapter 2 the probability distribution of the replenishment cycles can be proved as phase type on \([0, \infty)\) and is given by

\[ G(t) = 1 - e^{-(\lambda + \mu) t} \quad (6.18) \]

Therefore

\[ E(T) = \int_0^\infty e^{-\lambda t} \frac{1}{1 - e^{-\lambda t}} dt \quad (6.19) \]

\[ = -\alpha A^{-1} e \quad (6.20) \]
From (6.16), the theorem follows.

### 6.5 Optimization Problem

Let \( M_k \) represent the random variable of the re-ordering quantity of commodity \( C_k \), then

\[
E(M_k) = E(T) \left[ \lambda_k + \sum_{i_1=s_1+1}^{S_1} \sum_{i_2=s_2+1}^{S_2} \cdots \sum_{i_n=s_n+1}^{S_n} \pi_{i_1i_2\ldots i_n} \left( i_k \omega_k + \mu \sum_{j_k=0}^{i_k} j_k \left( \frac{i_k}{j_k} \right) p^{i_k-j_k} q^{j_k} \right) \right]
\]

where

\[
H_k(s^*, S^*) = \sum_{i_1=s_1+1}^{S_1} \sum_{i_2=s_2+1}^{S_2} \cdots \sum_{i_n=s_n+1}^{S_n} \sum_{i_{i_{i_2\ldots i_n}}}^{i_{i_{i_1i_2\ldots i_n}}} \pi_{i_1i_2\ldots i_n} i_k j_k
\]

(6.22)

Let \( h_k \) be the unit holding cost per unit time, \( c_k \) the unit procurement cost and \( d_k \) the unit damage cost of commodity \( C_k \) \((k = 1, 2, \ldots, n)\). Assume that the fixed ordering cost for placing an order is \( K \) irrespective of the number of different items ordered for replenishment. Therefore the cost function is

\[
C(s_1, s_2, \ldots, s_n, S_1, S_2, \ldots, S_n) = \frac{K + \sum_{k=1}^{n} c_k E(M_k)}{E(T)} + \sum_{k=1}^{n} [h_k + d_k \left( \omega_k + \mu q_k \right)] H_k(s^*, S^*)
\]

(6.23)

From (6.15) we get

\[
= \frac{K}{F(s^*, S^*)} + \sum_{k=1}^{n} [c_k \lambda_k + (c_k + d_k) \left( \omega_k + \mu q_k \right) + h_k] H_k(s^*, S^*)
\]
Since shortages are not allowed and lead time is assumed to be zero it is reasonable to expect that \( s_k = 0 \), \( (k = 1, 2, \ldots, n) \) for the optimum cost function.

**Theorem 6.4**

The cost function \( C(s_1, s_2, \ldots, s_n, S_1, S_2, \ldots, S_n) \) is minimum for \( s_1 = s_2 = \ldots = s_n = 0 \)

**Proof:**

Suppose \( s_1 > 0 \). Let \( s_1 = 1 + s_n + s_{n-1}M_n + s_{n-2}M_{n-1}M_n + \ldots + (s_1 - 1)M_2 \ldots M_n \)

Consider the matrix \( \tilde{A} = (\tilde{a}_{ij}, \ldots, \tilde{j}) \), \( (i_1, i_2, \ldots, i_n), (j_1, j_2, \ldots, j_n) \in E_0 \)

where

\[
\tilde{a}_{ij1, \ldots, j_n} = \begin{cases} 
\mu + \sum_{k=1}^{n} (\lambda - i_k \omega_k) & \text{if } i_k = j_k, k = 1, 2, \ldots, n \\
\mu \left( \prod_{k=1}^{i_1} p_{i_k}^{j_k} q_{i_k-j_k} \right) & \text{if } \sum_{k=1}^{n} (i_k - j_k) > 1 \\
0 & \text{otherwise}
\end{cases}
\]

(6.24)

Let \( \tilde{D}_i \) be the determinant of the submatrix obtained from \( \tilde{A} \) by deleting the first \( i^* - s_1^* + 1 \) rows, the last and first \( i^* - s_1^* \) columns \( (i^* \neq S^*) \), \( \tilde{D}_S = 1 \).

Then \( \tilde{D}_i = D_i \) for \( i^* \in E^* \) and \( \tilde{D}_i \) is positive for every \( i^* \).

From (6.15) we get
\[ F(s_1 - 1, s_2, \ldots, s_n, S_1, S_2, \ldots, S_n) = F(s^*_1, S^*) \]

\[ = \sum_{i^* = S_1}^{S^n} \frac{D_{i^*}}{\prod_{k^* = i^*} (-a_{k^*}, k^*)} \]

Let

\[ F(0, S^*) \] and \[ H_2(0, S^*) \]

Then (6.24) will become

\[ C(0, 0, \ldots, 0, S_1, S_2, \ldots, S_n) = \int \frac{K}{\mu} \, ds \]

6.6 NUMERICAL ILLUSTRATIONS

In this section we provide some numerical examples to illustrate the solutions obtained. We use the same parameters as in the previous section, except for the new parameter \( \mu \). The last three tables compare the optimum (\( S_1, S_2, S_3 \)) values of the inventory problem with the disaster rates \( \mu = 10, 20, 30, 40 \) respectively. Table 6.1 gives the optimum values of \( S_1, S_2, S_3 \) for the case when the disaster rates are \( \mu = 10, 20, 30, 40 \) respectively.

\[ H_1(s_1 - 1, s_2, \ldots, s_n, S_1, S_2, \ldots, S_n) = \sum_{i_1 = S_1}^{S_1} \sum_{i_2 = S_2 + 1}^{S_2} \ldots \sum_{i_n = S_n + 1}^{S_n} \frac{(i_1 - s_1 + s_1)D_{i^*}}{\prod_{k^* = i^*} (-a_{k^*}, k^*)} \]

\[ \leq s_1 + \sum_{i^* = S^*_1}^{S^*_1} \frac{(i_1 - s_1)D_{i^*}}{\prod_{k^* = i^*} (-a_{k^*}, k^*)} \quad \text{by (6.25)} \]

Thus, from (6.24) – (6.26) we have

\[ C(s_1 - 1, s_2, \ldots, s_n, S_1, S_2, \ldots, S_n) < C(s_1, s_2, \ldots, s_n, S_1, S_2, \ldots, S_n) \]

Therefore,

\[ C(0, s_2, \ldots, s_n, S_1, S_2, \ldots, S_n) < C(s_1, s_2, \ldots, s_n, S_1, S_2, \ldots, S_n) \]
If $s_k > 0$ for $k > 1$, then interchanging the position of $s_1$ and $s_k$ we can similarly prove that the cost function is minimum for $s_k = 0$ for each $k$. Hence the theorem.

Let $F(0, S^*) = \Phi(S^*)$ and $H_k(0, S^*) = \psi_k(S^*)$

Then (6.24) will become

$$C(0,0,...,0, S_1, S_2,..., S_n) = \frac{K}{\Phi(S^*)} + \sum_{k=1}^{n} \left[ c_k^k \lambda_k + \left( c_k + d_k \right) \left( \omega_k + \mu q_k \right) + h_k \right] \Psi_k(S^*)$$

(6.27)

6.6 NUMERICAL ILLUSTRATIONS

In this section we provide some numerical examples. Table 6.1 gives the optimum $(S_1, S_2, S_3)$ values of a three commodity problem when $\mu = 5$. Figure 6.1 depicts that optimum values of $S_1$ and $S_2$ decrease with the increase of value of $\mu$. The last three tables compare the optimum $(S_1, S_2)$ values of a two commodity inventory problem when the disaster rates are $\mu = 10, 5, 1$ respectively.

**Table 6.1**

(Optimum values of $(S_1, S_2, S_3)$)

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$\mu = 5$, $p_1 = 1$, $p_2 = 2$, $p_3 = 3$, $K = 100$, $c_1 = 25$, $c_2 = 10$, $c_3 = 30$, $h_1 = 5$, $h_2 = 2$, $h_3 = 6$, $d_1 = 5/3$, $d_2 = 2/3$, $d_2 = 2$. 
Figure 6.1
(Optimum values of $(S_1, S_2)$)

\[ \begin{align*}
\lambda_1 = 2, \; \lambda_2 = 1, \; \omega_1 = 0, \; \omega_2 = 0. \\
\end{align*} \]

Table 6.2
(Optimum values of $(S_1, S_2$ when $\mu = 10$)

\[ \begin{align*}
p_1 = 0.3, \; p_2 = 0.1, \; K = 100, \; c_1 = 20, \; c_2 = 10, \; h_1 = 4, \; h_2 = 2, \; d_1 = 4/3, \; d_2 = 2/3 \\
\end{align*} \]
Table 6.3

(Optimum values of $(S_1, S_2$ when $\mu = 5$)

\[ p_1 = .3, \ p_2 = .1, \ K = 100, \ c_1 = 20, \ c_2 = 10, \ h_1 = 4, \ h_2 = 2, \ d_1 = 4/3, \ d_2 = 2/3 \]

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Table 6.4

(Optimum values of $(S_1, S_2$ when $\mu = 1$)

\[ p_1 = .3, \ p_2 = .1, \ K = 100, \ c_1 = 20, \ c_2 = 10, \ h_1 = 4, \ h_2 = 2, \ d_1 = 4/3, \ d_2 = 2/3 \]

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