Research Article

EPQ Model for Trended Demand with Rework and Random Preventive Machine Time

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Economic production quantity (EPQ) inventory model for trended demand has been analyzed with rework facility and stochastic preventive machine time. Due to the complexity of the model, search method is proposed to determine the best optimal solution. A numerical example and sensitivity analysis are carried out to validate the proposed model. From the sensitivity analysis, it is observed that the rate of change of demand has significant impact on the optimal inventory cost. The model is very sensitive to the production and demand rate.

1. Introduction


In this paper, we analyze an economic production quantity (EPQ) model with rework and random preventive maintenance time together when demand is increasing function of time. The consideration of random preventive maintenance time, rework, and trended demand in the model increases its applicability in the electronic and automobile industries. In this production system, produced items are inspected immediately. Defective items are stocked and reworked at the end of the production uptime. We will call these items as recoverable items. Out of these recoverable items, the fraction of the items will be labeled as “new” and rest will be scrapped. Preventive maintenance is performed at the end of the rework process, and the maintenance time is assumed to be random. When demand is increasing, shortages may occur which will be treated as lost sales in this study. It is observed that the rate of change of demand has significant impact on the optimal
Table 1: Sensitivity analysis of $T_{1a}$ and total cost when preventive maintenance time is uniformly and exponentially distributed.

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<tr>
<th>Parameter</th>
<th>Percentage change</th>
<th>Uniform distribution $T_{1a}$</th>
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The status of the serviceable inventory is depicted in Figure 1. Production occurs during $[0, T_{1a}]$. In phase $x$ defective items per unit time are to be reworked. The rework process starts at the end of the predetermined production uptime. The rework time ends at $T_{3r}$ time period. The different production processes of the material and defective items result in different product rates. During the rework, some rejected and scrapped items will occur. LIFO policy is assumed for the production system. So, serviceable items during the rework uptime are utilized before the fresh items from the production in uptime. The new production run is started when the inventory level reaches zero at the end of $T_{2a}$ time period. It may happen that the production may not start at $T_{2a}$ time period because unavailability of the machine is randomly distributed with a probability density function $f(t)$. The nonavailability of machine may result in shortage during $T_3$ time period. The production will resume after the $T_3$ time period.

From the above description, the inventory level in a production uptime period is governed by the differential equation

$$\frac{dI_{1a}(t_{1a})}{dt_{1a}} = P - R(t_{1a}) - x, \quad 0 \leq t_{1a} \leq T_{1a}. \quad (1)$$

The inventory level in a rework uptime is

$$\frac{dI_{3r}(t_{3r})}{dt_{3r}} = P_1 - R(t_{3r}) - x_1, \quad 0 \leq t_{3r} \leq T_{3r}. \quad (2)$$

The inventory level in a production downtime is

$$\frac{dI_{2a}(t_{2a})}{dt_{2a}} = -R(t_{1a}), \quad 0 \leq t_{2a} \leq T_{2a}. \quad (3)$$

The inventory level in a rework downtime is

$$\frac{dI_{4r}(t_{4r})}{dt_{4r}} = -R(t_{4r}), \quad 0 \leq t_{4r} \leq T_{4r}. \quad (4)$$

inventory cost. It is suggested that when demand is trended, preventive maintenance time should be controlled by recruiting well-qualified technicians. The uniform distribution and exponential distribution for preventive maintenance time are explored. The paper is organized as follows: Section 2 is about the mathematical development of the proposed problem. In Section 3, example and sensitivity are given. Conclusions are highlighted in Section 4.

2. Mathematical Model

Assumptions. (1) The inventory system under consideration deals with single item. (2) Standard quality items must be greater than the demand. (3) The production and rework rates are constant. (4) The demand rate, $R(t) = a(1 + bt)$, is increasing function of time, where $a > 0$ is scale demand and $0 < b < 1$ denotes the rate of change of demand. (5) Setup cost for rework process is zero or negligible. (6) Recoverable items are spawned during the production uptime, and scrapped items are produced during the rework uptime.
Under the assumption of LIFO production system, the inventory level of good items depletes at a constant rate during rework uptime and downtime. The inventory level is governed by

\[
\frac{dI_{1a}(t_{3a})}{dt_{3a}} = 0, \quad 0 \leq t_{3a} \leq T_{3r} + T_{4r}.
\]  (5)

Using \(I_{1a}(0) = 0\), the solution of (1) is

\[
I_{1a}(t_{1a}) = (P - a - x) t_{1a} - \frac{abT_{1a}^2}{2}, \quad 0 \leq t_{1a} \leq T_{1a}
\]  (6)

which is the inventory level during \([0, T_{1a}]\). Hence, the total inventory in a production uptime is

\[
TI_{1a} = \int_0^{T_{1a}} I_{1a}(t_{1a}) \, dt_{1a}
\]  (7)

Using \(I_{3r}(0) = 0, I_{4r}(0) = 0\), the total inventory of serviceable items for the rework uptime and rework downtime is

\[
TI_{3r} = (P_1 - a - x_1) \frac{t_{3r}^2}{2} - \frac{abT_{3r}^3}{6},
\]

\[
TI_{4r} = \alpha \left[ \frac{t_{4r}^2}{2} + \frac{bT_{4r}^3}{3} \right],
\]  (8)

respectively.

Using \(I_{2a}(I_{2a}) = 0\), the total inventory level of a production downtime is

\[
TI_{2a} = \alpha \left[ \frac{t_{2a}^2}{2} + \frac{bT_{2a}^3}{3} \right].
\]  (9)

The maximum inventory is

\[
I_m = I_{1a}(T_{1a}) = (P - a - x) T_{1a} - \frac{abT_{1a}^2}{2}
\]  (10)

and hence, the total inventory in a rework uptime is

\[
TI_{3a} = I_m (T_{3a} + T_{4a}).
\]  (11)

Now, let us analyze the inventory level of recoverable items (Figure 2).

The inventory level of recoverable items in a production uptime is governed by the differential equation

\[
\frac{dI_{r1}(t_{r1})}{dt_{r1}} = x, \quad 0 \leq t_{r1} \leq T_{1a}.
\]  (12)

Since initially there are no recoverable items, that is, \(I_r(0) = 0\), the solution of (12) is

\[
I_{r1}(t_{r1}) = xt_{r1}, \quad 0 \leq t_{r1} \leq T_{1a}.
\]  (13)

Hence, the total inventory of recoverable items in a production uptime is

\[
TTI_{r1} = \frac{xT_{1a}^2}{2}
\]  (14)

and the maximum recoverable inventory is

\[
I_{Mr} = I_{r1}(T_{1a}) = xT_{1a}.
\]  (15)

The inventory level of recoverable item in the rework uptime is modeled as

\[
\frac{dI_{r3}(t_{r3})}{dt_{r3}} = -P_1, \quad 0 \leq t_{r3} \leq T_{3r}.
\]  (16)

Using \(I_{r3}(T_{3r}) = 0\), the inventory level of recoverable item in rework uptime is

\[
I_{r3}(t_{r3}) = P_1 (T_{3r} - t_{r3}), \quad 0 \leq t_{r3} \leq T_{3r}.
\]  (17)

Hence, the total inventory of recoverable item in the rework uptime is

\[
TTI_{r3} = \frac{P_1T_{3r}^2}{2}.
\]  (18)

The number of recoverable inventories is

\[
I_{Mr} = I_{r3}(0) = P_1 T_{3r}.
\]  (19)

Hence,

\[
T_{3r} = \frac{I_{Mr}}{P_1}.
\]  (20)

Substituting \(I_{3r}\) from (15), we get

\[
T_{3r} = \frac{xT_{1a}}{P_1}.
\]  (21)

Hence, the total recoverable inventory is

\[
I_w = TTI_{r1} + TTI_{r3} = \frac{xT_{1a}^2}{2} \left( 1 + \frac{x}{P_1} \right).
\]  (22)
The inventory level at the beginning of the production downtime is equal to the inventory level at the end of the production uptime; that is,

\[ I_{1aT} = I_{2a}(0) \]  

Therefore,

\[ T_{2a} = \frac{1}{a} \left( (P - a - x) T_{1a} - \frac{ab}{2} T_{1a}^2 \right) \]  

(24)

When \( t_{3r} = T_{3r} \) and \( t_{4r} = 0 \), the inventory level for serviceable item in reorder process satisfies

\[ (P_i - a - x_i) T_{3r} - \frac{ab}{2} T_{3r}^2 = a \left( T_{4r} - \frac{b}{2} T_{4r}^2 \right) \]  

(25)

Neglecting \( T_{4r}^2 \) (because \( 0 < T_{4r} < 1 \)), we get

\[ T_{4r} = \frac{1}{a} (P_i - a - x_i) \frac{X_i}{P_i} T_{1a} \]  

(26)

The total production inventory cost is the sum of the production set up cost, inventory cost of serviceable item, inventory cost of recoverable item, and scrap cost:

\[ TC = A + h [TI_{1a} + TI_{3r} + TI_{2a} + TI_{4r} + TI_{3a}] + h_1 I_w + S_C x_i T_{3r} \]  

(27)

and the total cycle time is

\[ T = T_{1a} + T_{3r} + T_{2a} + T_{4r} \]  

(28)

Hence, the total cost per unit time without lost sales is given by

\[ TCT_{NL} = \frac{TC}{T} \]  

(29)

The optimal production uptime for the EPQ system without lost sales can be obtained by setting

\[ \frac{dTCT_{NL}(T_{1a})}{dT_{1a}} = 0. \]  

(30)

When unavailability time of a machine is longer than the production downtime duration, lost sales will occur. So the total inventory cost is

\[ E(TC) = A + h [TI_{1a} + TI_{3r} + TI_{2a} + TI_{4r} + TI_{3a}] + h_1 I_w + S_C x_i T_{3r} + S_L \]  

\[ \times \int_{t=T_{2a}+T_{4r}}^{\infty} R(t) \left( t - (T_{2a} + T_{4r}) \right) f(t) \, dt \]  

(31)

and the total cycle time for lost sales is

\[ E(T) = T_{1a} + T_{3r} + T_{2a} + T_{4r} \]  

\[ + \int_{t=T_{2a}+T_{4r}}^{\infty} (t - (T_{2a} + T_{4r})) f(t) \, dt. \]  

(32)

Hence, the total cost per unit time for lost sales is

\[ E(TCT) = \frac{E(TC)}{E(T)}. \]  

(33)

We discuss lost sales scenario for two distributions, namely uniform distribution and exponential distribution.

### 2.1 Uniform Distribution

Define the probability distribution function \( f(t) \), when the preventive maintenance time \( t \) is distributed uniformly as follows:

\[ f(t) = \begin{cases} 
\frac{1}{\tau}, & 0 \leq t \leq \tau \\
0, & \text{otherwise.} 
\end{cases} \]  

(34)

Substituting \( f(t) \) in (33) gives the total cost per unit time for uniform distribution as

\[ TCT_U = \left( A + h [TI_{1a} + TI_{3r} + TI_{2a} + TI_{4r} + TI_{3a}] + h_1 I_w \right. \]

\[ + S_C x_i T_{3r} + S_L \int_{t=0}^{\tau} \left( \frac{a (1 + bt)}{\tau} \right) \left( t - (T_{2a} + T_{4r}) \right) \, dt \]

\[ \times \int_{t=T_{2a}+T_{4r}}^{\tau} \left( t - (T_{2a} + T_{4r}) \right) \, dt \]  

\[ \approx 1 \]  

(35)

substituting all the time variables in (35) in terms of \( T_{1a} \), the objective function; \( TCT_{NL} \) is a function of \( T_{1a} \) only. The optimum value of \( T_{1a} \) can be computed by setting

\[ \frac{dTCT_U(T_{1a})}{dT_{1a}} = 0. \]  

(36)

To derive the best solution from nonlost sales and lost sales scenarios, we propose the following steps [17].

**Step 1.** Calculate (30), (24), and (26) and set \( T_{sb} = T_{2a} + T_{4r} \).

**Step 2.** If \( T_{sb} < \tau \), then the obtained solution is not feasible, and go to Step 3; otherwise the solution is obtained.

**Step 3.** Set \( T_{sb} = \tau \). Find \( T_{1aub} \) using (26) and (24). Calculate \( TCT_{NL}(T_{1aub}) \) using (29).

**Step 4.** Calculate (36), (24), and (26) and set \( T_{sb} = T_{2a} + T_{4r} \).

**Step 5.** If \( T_{sb} \geq \tau \), then \( T_{1aub}^* = T_{1aub} \) and the corresponding total cost is \( TCT_{NL}(T_{1aub}) \); otherwise, calculate \( TCT_U(T_{1aub}) \).

**Step 6.** If \( TCT_{NL}(T_{1aub}) \leq TCT_U(T_{1a}) \), then \( T_{1a}^* = T_{1aub} \); otherwise \( T_{1a}^* = T_{1a} \).

### 2.2 Exponential Distribution

Define the probability distribution function \( f(t) \), when the preventive maintenance time \( t \) is distributed exponential with mean \( 1/\lambda \) as

\[ f(t) = \lambda e^{-\lambda t}, \quad \lambda > 0. \]  

(37)
Here, the total cost per unit time for the lost sale $S_L$ is
\[
TCT_E = \left( A + h \left[ TI_{1a} + TI_{3r} + TI_{2a} + TI_{4r} + TI_{3s} \right] \\
+ h_1 T_{3r} + h_1 S_L x_1 T_{3r} \\
+ S_L \int_{T_T = T_{2a} + T_{4r}}^{\infty} R(t) \left( t - (T_{2a} + T_{4r}) \right) \lambda e^{-\lambda t} dt \right) \\
\times \left( T_{1a} + T_{3r} + T_{2a} + T_{4r} + \left( \frac{1}{\lambda} \right) e^{-\lambda (T_{2a} + T_{4r})} \right)^{-1}.
\]
\text{(38)}

Arguing as in (Section 2.1), we can obtain optimum total cost. The high nonlinearity of the cost functions (29), (35), and (38) does not guarantee that the optimal solution is global. However, using parametric values, convexity of the objective function is established.

3. Numerical Examples and Sensitivity Analysis

Consider, following parametric values to study the working of the proposed problem. Let $A = $200 per production cycle, $P = 10,000$ units per unit time, $a = 5000$ units per unit time, $b = 10\%$, $x = 500$ units per unit time; $x_1 = 400$ units per unit time, $h = $5 per unit per unit time, $h_1 =$...
In this research, rework of imperfect quality and random preventive maintenance time are incorporated in economic production quantity model when demand increases with time. The random preventive maintenance time is distributed uniformly and exponentially. The models are validated by the example. The sensitivity analysis suggests that the optimal total cost per unit time is sensitive to changes in the production rate, the demand rate, and the product defect rate in both the uniform and the exponential distributed preventive maintenance time. To combat increasing demand, the management should adopt the latest machinery which decreases defective production rate, reducing rework, and as a consequence, the machine's production uptime can be utilized to its utmost. Further research can be carried out to study the effect of deterioration of units.

4. Conclusions

In this research, rework of imperfect quality and random preventive maintenance time are incorporated in economic production quantity model when demand increases with time. The random preventive maintenance time is distributed uniformly and exponentially. The models are validated by the example. The sensitivity analysis suggests that the optimal total cost per unit time is sensitive to changes in the production rate, the demand rate, and the product defect rate in both the uniform and the exponential distributed preventive maintenance time. To combat increasing demand, the management should adopt the latest machinery which decreases defective production rate, reducing rework, and as a consequence, the machine's production uptime can be utilized to its utmost. Further research can be carried out to study the effect of deterioration of units.
\( P \): Production rate  
\( P_1 \): Rework process rate  
\( R = R(t) \): Demand rate; \( a(1+bt), a > 0, 0 < b < 1 \)  
\( x \): Product defect rate  
\( x_1 \): Product scrap rate  
\( A \): Production setup cost  
\( h \): Serviceable items holding cost  
\( h_1 \): Recoverable items holding cost  
\( S_C \): Scrap cost  
\( S_L \): Lost sales cost  
\( T_C \): Total inventory cost  
\( T \): Cycle time  
\( TCT \): Total inventory cost per unit time for lost sales model  
\( TCT_{NL} \): Total inventory cost per unit time for lost sales model with imperfect-quality items and two-way imperfect inspection and backlogging.  
\( TCT_U \): Total inventory cost per unit time for without lost sales model  
\( TCT_E \): Total inventory cost per unit time for lost sales model with exponential distribution preventive maintenance time.

References


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