

1- 2_Applied_Mathematical_Mod elling_2011.pdf *by*

Submission date: 26-Aug-2022 12:39PM (UTC+0700)

Submission ID: 1887302471

File name: 1-2_Applied_Mathematical_Modelling_2011.pdf (644.67K)

Word count: 5756

Character count: 27359



Optimal deteriorating items production inventory models with random machine breakdown and stochastic repair time

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ARTICLE INFO

Article history:

Received 12 October 2009

Received in revised form 17 December 2010

Accepted 11 January 2011

Available online 19 January 2011

Keywords:

Inventory

Machine breakdown

Deteriorating items

Stochastic repair time

ABSTRACT

This study develops deteriorating items production inventory models with random machine breakdown and stochastic repair time. The model assumes the machine repair time is independent of the machine breakdown rate. The classical optimization technique is used to derive an optimal solution. A numerical example and sensitivity analysis are shown to illustrate the models. The stochastic repair models with uniformly distributed repair time tends to have a larger optimal total cost than the fixed repair time model, however the production up time is less than the fixed repair time model. Production and demand rate are the most sensitive parameters for the optimal production up time, and demand rate is the most sensitive parameter to the optimal total cost for the stochastic model with exponential distribution repair time.

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1. Introduction

The production inventory problem has been investigated in recent years, and increasing number of researchers analyzes machine breakdown effect in production inventory problem. The effects of machine breakdown and corrective maintenance on the economic lot sizing were studied by Groenevelt et al. [1]. Groenevelt et al. [2] did similar research and included safety stocks to meet the service level. Moinezhadeh and Aggarwal [3] proposed an (s, S) model assuming the time between breakdowns is exponentially distributed, the restoration times are constant and excess demand is backordered. The research was extended by Arreola-Risa and DeCroix [4] who assumed shortages are partially backordered. Abboud [5] later extended the research by Groenevelt et al. [1]. In his model, he assumed machine failure may occur during production. When a machine fails, it will be repaired immediately. He assumed that repair times are independent and identically distributed. Giri et al. [6] developed EMQ model with machine failure and general repair time. They proposed a model to determine the production rate and production lot size to minimize the annual expected total cost.

Recently, many researchers extended the production inventory with machine breakdown model by considering other problems in production such as deterioration, preventive maintenance and rework. In the deteriorating production process, the process may move from an in-control state to an out-of-control state, and produces some proportion of defective item. Kim and Hong [7] developed Economic Manufacturing Quantity (EMQ) model with three deteriorating processes. Wang [8] developed an EPQ mathematical model where production shifts from an in-control state to an out-of-control state with a general shift distribution. Sana et al. [9] developed a production-inventory model with imperfect production process and some of the imperfect quality items can be sold at a reduced selling price. Similar method with reduction in demand rate and selling price were

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developed by Sana et al. [10]. Chakraborty et al. [11] developed an EPQ model considering production system that may shift from an in-control state to an out-of-control state or may breakdown at any random time during a production period. Similar to Chakraborty et al. [11] and assuming the defective items are reworked immediately, Sana [12] considered production shifts from an in-control state to an out-of-control state. The percentage of defective items is assumed varies non-linearly with the production rate and the production-run-time. Sana [13] developed a production-inventory model by considering imperfect production process, finite planning horizon, and varying production rate.

Preventive maintenance is usually used to reduce machine breakdown. Incorporated preventive maintenance to production inventory model was done by Cheung and Hausman [14]. They developed a mathematical model with random machine breakdowns and considered preventive maintenance and safety stock. Later Dohi et al. [15] extended the research by extending the model by Cheung and Hausman [14] to consider the stochastic nature of the model. Giri and Dohi [16] developed EMQ model with random variables corrective and preventive repair. They proposed solution procedure and computational algorithms to find the optimal production rate and lot size. El-Ferik [17] developed an EPQ model for unreliable manufacturing facility. Similar research for EPQ model with imperfect process has been done by Liao et al. [18]. Chiu et al. [19] developed an EPQ model with scrap, rework and stochastic machine breakdowns.

Deterioration is defined as decay, evaporation, obsolescence, and loss of quality marginal value of commodity that result in decreasing usefulness from its original condition. Some items like vegetables, milk, and fruits have deteriorating characteristics. Many researchers focus their study on deteriorating item, such as Balkhi [20], Chang et al. [21] and Roy et al. [22]. Misra [23] developed an EPQ for deteriorating items model and Wee [24] extended the model by considering partial backorder. Sana et al. [25] developed an economic production lot size model (EPLS) model for a deteriorating item with a linearly time-varying demand rate and shortages are allowed. Liao [26] developed a production inventory model for deteriorating item taking into consideration the effect of permissible delay in payment. An EPQ model for deteriorating production equipment and items was developed by Alfares et al. [27]. In their model, they also considered quality, inspection and maintenance, varying demand and production rates. Lo et al. [28] developed integrated production and inventory model. The model assumed varying deterioration rate, partial backordering, inflation, imperfect production process and multiple deliveries.

From the authors' literature search, very few researchers have considered production inventory model with deteriorating item and stochastic machine breakdown. Lin and Gong [29] developed EPQ deteriorating inventory model with machine breakdown and fix repair time. In real life, most repair times are stochastic. This paper extends the excellent research initiated by Lin and Gong [29]. Here, two models are developed: one model assumes repair time is uniformly distributed and the other model assumes repair time is exponentially distributed. The paper has four sections. The first section discusses the research motivation and literature review. The second section is model development. Section three shows an example and sensitivity analysis, and the final section is the concluding remarks.

2. Model development

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The assumptions:

1. Production rate is greater than demand rate.
2. Production and demand rate are constant.
3. Deteriorating rate is constant.
4. There is no repair or replacement for a deteriorated item.
5. Machine repair time is independent of machine breakdown.

Notations:

I	inventory level
I_1	inventory level in a production period
I_1	inventory level in a non-production period
T_1	production period
T_2	non-production period
T_3	shortage period
T_p	machine breakdown period
p	production rate
d	demand rate
θ	deteriorating rate
K	setup cost
h	holding cost
S	lost sales cost
π	deteriorating cost
M	repair machine cost

The inventory policy for lost sales case is illustrated in Fig. 1. When the machine does not breakdown during the production period, the production is performed during T_1 time period. When the inventory level reaches maximum level I_m , the production stops and inventory decreases due to demand and deterioration. The inventory level reaches zero units at time $(T_1 + T_2)$, and machine starts to produce the item again. Since the machine has a possibility of breakdown, the machine may not run the whole T_1 period. When breakdown occurs, the production period turns to T_p . When a machine breaks down, it will require some repair time. Since repair time is stochastic in $(T_2 + T_3)$ period, production may not always be possible and lost sales may occur during T_3 period.

The number of inventory in production period from the problem above can be formulated as:

$$\frac{dI_1(t_1)}{dt_1} + \theta I_1(t_1) = p - d, \quad 0 \leq t_1 \leq T_1. \quad (1)$$

While the number of inventory level in non-production period is represented by the following equation:

$$\frac{dI_2(t_2)}{dt_2} + \theta I_2(t_2) = -d, \quad 0 \leq t_2 \leq T_2. \quad (2)$$

Since $I_1(0) = 0$, and $I_2(T_2) = 0$, the inventory level in production period and non-production period are:

$$I_1(t_1) = \frac{p-d}{\theta} (1 - e^{-\theta t_1}), \quad 0 \leq t_1 \leq T_1, \quad (3)$$

$$I_2(t_2) = \frac{d}{\theta} (e^{\theta(T_2-t_2)} - 1), \quad 0 \leq t_2 \leq T_2. \quad (4)$$

Since $I_1 = I_2$ when $t_1 = T_1$ and $t_2 = 0$ then one has:

$$\frac{p-d}{\theta} (1 - e^{-\theta T_1}) = \frac{d}{\theta} (e^{\theta T_2} - 1). \quad (5)$$

Using the Taylor series approximation (Yang and Wee [30]), one has:

$$(p-d) \left(T_1 - \frac{1}{2} \theta T_1^2 \right) = d \left(T_2 + \frac{1}{2} \theta T_2^2 \right). \quad (6)$$

Since θT_2 is a small number, T_2 in terms of T_1 can be approximated as:

$$T_2 \cong \frac{(p-d) T_1 (1 - \frac{1}{2} \theta T_1)}{d}. \quad (7)$$

This approximation is commonly used in deteriorating production inventory problem (see Misra [23]). The expected inventory level can be expressed by the following:

$$E(I) = \int_{t=0}^{T_1} \frac{p-d}{\theta} (1 - e^{-\theta t_1}) + \int_{t=0}^{T_2} \frac{d}{\theta} (e^{\theta(T_2-t_2)} - 1), \quad (8)$$

$$E(I) = \frac{p-d}{\theta^2} (\theta T_1 + e^{-\theta T_1} - 1) + \frac{d}{\theta^2} (-\theta T_2 + e^{\theta T_2} - 1).$$

Using Taylor series approximation, (8) can be written as:

$$E(I) = (p-d) \left(\frac{T_1^2}{2} \right) + d \left(\frac{T_2^2}{2} \right). \quad (9)$$

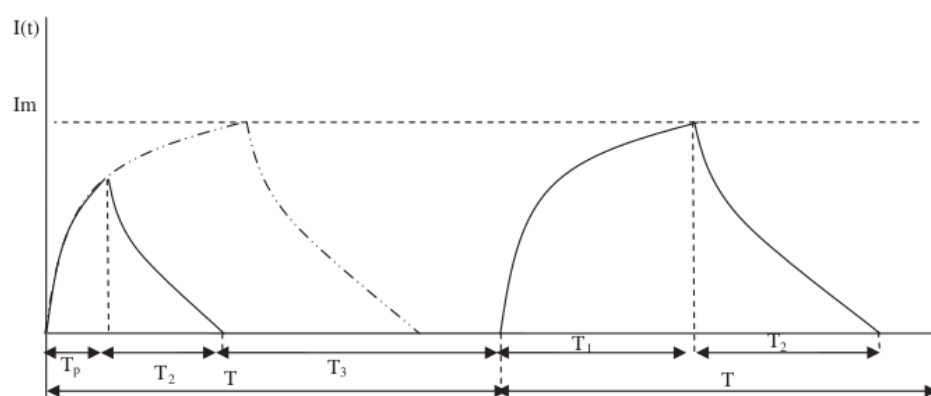


Fig. 1. Inventory system for the case with lost sales.

Using Taylor's series expansion for small value of θT , e^x is approximated as $1 + x + x^2/2$. The percentage error for the fourth term in the Taylor series can be modeled as: $\frac{\frac{1}{2}(\theta T)^3}{1 + \theta T + \frac{1}{2}(\theta T)^2 + \frac{1}{3}(\theta T)^3}$. The percentage error is about 0.2% when $\theta T = 0.25$. Since neglecting the terms higher than the fourth term will result in even smaller error, therefore the four terms and higher can be neglected.

Substitute (7) to (9), one has:

$$E(I) = p - d \left(\frac{T_1^2}{2} \right) + d \left(\frac{(p-d)T_1(1 - \frac{1}{2}\theta T_1)}{2d} \right)^2. \quad (10)$$

Since $\frac{1}{2}\theta T_1$ is very small, (10) can be simplified as:

$$E(I) = \frac{p^2}{2d} \left(1 - \frac{d}{p} \right) T_1^2. \quad (11)$$

Since there is breakdown machine possibilities, then (11) can be formulated as:

$$E(I) \cong \begin{cases} \frac{p^2}{2d} \left(1 - \frac{d}{p} \right) T_p^2, & \text{for } T_p \leq T_1, \\ \frac{p^2}{2d} \left(1 - \frac{d}{p} \right) T_1^2, & \text{for } T_p > T_1. \end{cases} \quad (12)$$

Here, similar breakdown machine probability density function as Lin and Gong [29] is used. The function of T_p is equal to $f(T_p) = \mu e^{-\mu T_p}$, for $T_p > 0$. The expected inventory can be written as:

$$E(I) = \int_{T_p=0}^{T_1} \frac{p^2}{2d} \left(1 - \frac{d}{p} \right) T_p^2 \mu e^{-\mu T_p} + \int_{T_p=T_1}^{\infty} \frac{p^2}{2d} \left(1 - \frac{d}{p} \right) T_1^2 \mu e^{-\mu T_p}, \quad (13)$$

$$E(I) = \frac{p(p-d)(1 - e^{-\mu T_1} - \mu T_1 e^{-\mu T_1})}{\mu^2 d}.$$

The expected deteriorated item can be formulated as:

$$E(R) = pT_1 - d(T_1 + T_2). \quad (14)$$

Substitute T_2 from (7) to (14), then it can be simplified as:

$$E(R) \cong \begin{cases} \frac{p}{2} \left(1 - \frac{d}{p} \right) \theta T_p^2, & \text{for } T_p \leq T_1, \\ \frac{p}{2} \left(1 - \frac{d}{p} \right) \theta T_1^2, & \text{for } T_p > T_1. \end{cases} \quad (15)$$

Using the similar function of T_p , the expected deteriorating item can be written as:

$$E(R) = \int_{T_p=0}^{T_1} \frac{p}{2} \left(1 - \frac{d}{p} \right) \theta T_p^2 \mu e^{-\mu T_p} + \int_{T_p=T_1}^{\infty} \frac{p}{2} \left(1 - \frac{d}{p} \right) \theta T_1^2 \mu e^{-\mu T_p}, \quad (16)$$

$$E(R) = \frac{(p-d)\theta(1 - e^{-\mu T_1} - \mu T_1 e^{-\mu T_1})}{\mu^2}.$$

The corrective cost can be formulated as:

$$E(Mc) = M(1 - e^{-\mu T_1}). \quad (17)$$

The total inventory cost of lost sales case consists of setup cost, corrective cost, holding cost, deteriorating cost and lost sales cost. Lost sales occur when machine repair time period is longer than non-production time period. The total inventory cost can be expressed as:

$$TC(T_1, T_2) = E \left[K + M(1 - e^{-\mu T_1}) + hE(I) + \pi E(R) + Sd \int_{T_p=0}^{T_1} \int_{t=T_2}^{\infty} (t - T_2)f(t)\mu e^{-\mu T_p} dt dT_p \right],$$

$$TC(T_1, T_2) = E \left[K + M(1 - e^{-\mu T_1}) + \left(h \frac{p}{d} + \pi \theta \right) \left(\frac{(p-d)(1 - e^{-\mu T_1} - \mu T_1 e^{-\mu T_1})}{\mu^2} \right) + Sd \int_{T_p=0}^{T_1} \int_{t=T_2}^{\infty} (t - T_2)f(t)\mu e^{-\mu T_p} dt dT_p \right]. \quad (18)$$

The total replenishment time is equal to the production up time period, non-production period and repair time probability. The expected total replenishment time can be formulated as:

$$E(T) = \int_{T_p=0}^{T_1} \left(T_1 + T_2 + \int_{t=T_2}^{\infty} (t - T_2)f(t)dt \right) \mu e^{-\mu T_p} dT_p. \quad (19)$$

The expected T_1 and T_2 time period can be written as:

$$E(T_1 + T_2) = \int_{T_p=0}^{T_1} \left(1 + (p-d) \frac{(1-0.5\theta T_p)}{d} \right) T_p \mu e^{-\mu T_p} dT_p + \int_{T_p=T_1}^{\infty} \left(1 + (p-d) \frac{(1-0.5\theta T_1)}{d} \right) T_1 \mu e^{-\mu T_p} dT_p, \quad (20)$$

$$E(T_1 + T_2) = \frac{p(1-e^{-\mu T_1})}{d\mu}.$$

Substitute (20) to (19), one has:

$$E(T) = \frac{p(1-e^{-\mu T_1})}{d\mu} + \int_{T_p=0}^{T_1} \int_{t=T_2}^{\infty} (t-T_2)f(t)\mu e^{-\mu T_p} dt dT_p. \quad (21)$$

Using the renewal reward theorem, the expected total cost per unit time can be formulated as follows:

$$TCT = \frac{E(TC)}{E(T)}. \quad (22)$$

Combine (18) and (21), we have the expected total cost per unit time as follows:

$$TCT(T_1, T_2) = \frac{K + M(1-e^{-\mu T_1}) + \left(h \frac{p}{d} + \pi\theta \right) \left(\frac{(p-d)(1-e^{-\mu T_1}-\mu T_1 e^{-\mu T_1})}{\mu^2} \right) + Sd \int_{T_p=0}^{T_1} \int_{t=T_2}^{\infty} (t-T_2)f(t)\mu e^{-\mu T_p} dt dT_p}{\frac{p(1-e^{-\mu T_1})}{d\mu} + \int_{T_p=0}^{T_1} \int_{t=T_2}^{\infty} (t-T_2)f(t)\mu e^{-\mu T_p} dt dT_p}. \quad (23)$$

2.1. Uniform distribution case

Assume that the machine repair time t , is a random variable that is uniformly distributed over the interval $[0, b]$. The probability density function, $f(t)$, is given as:

$$f(t) = \begin{cases} 1/b, & 0 \leq t \leq b, \\ 0, & \text{otherwise.} \end{cases} \quad (24)$$

Substitute uniform probability density function in (24) to (23), one has:

$$TCT(T_1, T_2) = \frac{K + M(1-e^{-\mu T_1}) + \left(h \frac{p}{d} + \pi\theta \right) \left(\frac{(p-d)(1-e^{-\mu T_1}-\mu T_1 e^{-\mu T_1})}{\mu^2} \right) + \frac{Sd}{b} \int_{T_p=0}^{T_1} \int_{t=T_2}^b (t-T_2)\mu e^{-\mu T_p} dt dT_p}{\frac{p(1-e^{-\mu T_1})}{d\mu} + \frac{1}{b} \int_{T_p=0}^{T_1} \int_{t=T_2}^b (t-T_2)\mu e^{-\mu T_p} dt dT_p}. \quad (25)$$

The expected shortage can be written as:

$$E(T_3) = \frac{1}{b} \int_{T_p=0}^{T_1} \int_{t=T_2}^b (t-T_2)\mu e^{-\mu T_p} dt dT_p,$$

$$E(T_3) = \int_{T_p=0}^{T_1} \frac{\left(b - \frac{(p-d)T_p(1-\frac{1}{2}\theta T_p)}{d} \right)^2}{2b} \mu e^{-\mu T_p} dT_p. \quad (26)$$

Simplify equation above, one has:

$$E(T_3) = \int_{T_p=0}^{T_1} \frac{\left(b - \frac{(p-d)T_p}{d} \right)^2}{2b} \mu e^{-\mu T_p} dT_p,$$

$$E(T_3) = \frac{((b\mu d)^2 - 2b(p-d)\mu d + 2(p-d)^2)(1-e^{-\mu T_1}) - e^{-\mu T_1} \mu T_1(p-d)((p-d)(2\mu T_1) - 2b\mu d)}{2b\mu^2 d^2}. \quad (27)$$

Substitute (27) to (25), the total cost per unit time of uniform distribution repair time is:

$$TCT(T_1) = \frac{K + M(1-e^{-\mu T_1}) + h \frac{p(p-d)(1-e^{-\mu T_1}-\mu T_1 e^{-\mu T_1})}{\mu^2 d} + \pi\theta \frac{(p-d)\theta(1-e^{-\mu T_1}-\mu T_1 e^{-\mu T_1})}{\mu^2}}{\frac{p(1-e^{-\mu T_1})}{d\mu} + \frac{((b\mu d)^2 - 2b(p-d)\mu d + 2(p-d)^2)(1-e^{-\mu T_1}) - e^{-\mu T_1} \mu T_1(p-d)((p-d)(2\mu T_1) - 2b\mu d)}{2b\mu^2 d^2}} + \frac{Sd \left(\frac{((b\mu d)^2 - 2b(p-d)\mu d + (p-d)^2)(1-e^{-\mu T_1}) - e^{-\mu T_1} \mu T_1(p-d)((p-d)(2\mu T_1) - 2b\mu d)}{2b\mu^2 d^2} \right)}{\frac{p(1-e^{-\mu T_1})}{d\mu} + \frac{((b\mu d)^2 - 2b(p-d)\mu d + 2(p-d)^2)(1-e^{-\mu T_1}) - e^{-\mu T_1} \mu T_1(p-d)((p-d)(2\mu T_1) - 2b\mu d)}{2b\mu^2 d^2}}. \quad (28)$$

Differentiate (28) with respect to T_1 , one has:

$$\frac{dTCT(T_1)}{dT_1} = \frac{M\mu e^{-\mu T_1} + (h_d^p + \pi\theta)((p-d)T_1 e^{-\mu T_1})}{\frac{p(1-e^{-\mu T_1})}{d\mu} + \frac{((b\mu d)^2 - 2b(p-d)\mu d + 2(p-d)^2)(1-e^{-\mu T_1}) - e^{-\mu T_1} \mu T_1 ((p-d)((p-d)(2+\mu T_1) - 2b\mu d))}{2b\mu^2 d^2}} - \frac{\frac{S\mu^3 e^{-\mu T_1} (bd(-bd+2(p-d)T_1) - T_1^2(p-d)^2)}{2db\mu^2}}{\frac{p(1-e^{-\mu T_1})}{d\mu} + \frac{((b\mu d)^2 - 2b(p-d)\mu d + 2(p-d)^2)(1-e^{-\mu T_1}) - e^{-\mu T_1} \mu T_1 ((p-d)((p-d)(2+\mu T_1) - 2b\mu d))}{2b\mu^2 d^2}} - \frac{A \left(K + M(1 - e^{-\mu T_1}) - \frac{(h_d^p + \pi\theta)((p-d)(\mu T_1 e^{-\mu T_1} + e^{-\mu T_1} - 1))}{\mu^2} \right)}{\left(\frac{p(1-e^{-\mu T_1})}{d\mu} + \frac{((b\mu d)^2 - 2b(p-d)\mu d + 2(p-d)^2)(1-e^{-\mu T_1}) - e^{-\mu T_1} \mu T_1 ((p-d)((p-d)(2+\mu T_1) - 2b\mu d))}{2b\mu^2 d^2} \right)^2} - \frac{A \left(Sd \left(\frac{((b\mu d)^2 - 2b(p-d)\mu d + 2(p-d)^2)(1-e^{-\mu T_1}) - e^{-\mu T_1} \mu T_1 ((p-d)((p-d)(2+\mu T_1) - 2b\mu d))}{2b\mu^2 d^2} \right) \right)}{\left(\frac{p(1-e^{-\mu T_1})}{d\mu} + \frac{((b\mu d)^2 - 2b(p-d)\mu d + 2(p-d)^2)(1-e^{-\mu T_1}) - e^{-\mu T_1} \mu T_1 ((p-d)((p-d)(2+\mu T_1) - 2b\mu d))}{2b\mu^2 d^2} \right)^2}, \quad (29)$$

where:

$$A = \frac{(\mu^3 e^{-\mu T_1} (bd(-bd + T_1(p-d)(2 - (p-d))))}{2b\mu^2 d^2},$$

Property 1. For a function $f: S \rightarrow R_1$ defined by $f(x) = g(x)/h(x)$ where $g: S \rightarrow R_1$ and $h: S \rightarrow R_1$, and S is a non-empty convex set in E_n . The following discuss convexity and concavity functions:

- (a) g is convex on S , and $g(x) \geq 0$ for each $x \in S$.
- (b) h is concave on S , and $h(x) \geq 0$ for each $x \in S$, and
- (c) Both g and h are differentiable.

Using Property 1, the total cost per unit time is convex where $0 \leq T_2 \leq b$, and

$$M < \frac{(hp + \pi d\theta)(8(p-d) - 4b\mu d(2 + b\theta)) - S\mu b d\theta(4(p-d) + \mu b^2 d\theta)}{\mu^2 d}.$$

Detailed calculation is shown in Appendix A.

2.2. Exponential distribution case

In the second case, the machine repair time is a random variable that is exponentially distributed. Exponential probability density function with mean $\frac{1}{\lambda}$, is given as:

$$f(t) = \lambda e^{-\lambda t} \text{ for } \lambda > 0.$$

The expected shortage period is:

$$E(T_3) = \int_{T_p=0}^{T_1} \int_{t=T_2}^{\infty} (t - T_2) \lambda e^{-\lambda t} \mu e^{-\mu T_p} dt dT_p, \quad (30)$$

$$E(T_3) = \frac{e^{T_1 \left(\frac{\lambda(p-d)}{2d}(-2+\theta T_1) + \frac{\lambda p}{d} + \mu \right)} - e^{T_1 \left(\frac{T_1 p \theta}{2d} + 1 - \frac{\theta T_1}{2} \right)}}{e^{T_1 \left(\frac{\lambda p}{d} + \mu \right)}}.$$

From (30), the value of the exponential distribution expected total time can be expressed as:

$$E(T) = E(T_1 + T_2) + E(T_3), \quad (31)$$

$$E(T) = \frac{p(1 - e^{-\mu T_1})}{d\mu} + \frac{e^{T_1 \left(\frac{\lambda(p-d)}{2d}(-2+\theta T_1) + \frac{\lambda p}{d} + \mu \right)} - e^{T_1 \left(\frac{T_1 p \theta}{2d} + 1 - \frac{\theta T_1}{2} \right)}}{e^{T_1 \left(\frac{\lambda p}{d} + \mu \right)}}.$$

The total cost for exponential distribution case can be formulated by substituting (31) into (23), and one has:

$$TCT(T_1) = \frac{K + M(1 - e^{-\mu T_1}) + (h_d^p + \pi\theta) \left(\frac{(p-d)(1 - e^{-\mu T_1} - \mu T_1 e^{-\mu T_1})}{\mu^2} \right)}{\frac{p(1 - e^{-\mu T_1})}{d\mu} + \frac{e^{T_1 \left(\frac{\lambda(p-d)}{2d}(-2+\theta T_1) + \frac{\lambda p}{d} + \mu \right)} - e^{T_1 \left(\frac{T_1 p \theta}{2d} + 1 - \frac{\theta T_1}{2} \right)}}{e^{T_1 \left(\frac{\lambda p}{d} + \mu \right)}}} + \frac{Sd \left(\frac{-e^{T_1 \left(\frac{T_1 p \theta}{2d} + 1 - \frac{\theta T_1}{2} \right)} + e^{T_1 \left(\frac{\lambda(p-d)}{2d}(-2+\theta T_1) + \frac{\lambda p}{d} + \mu \right)}}{e^{T_1 \left(\frac{\lambda p}{d} + \mu \right)}} \right)}{\frac{p(1 - e^{-\mu T_1})}{d\mu} + \frac{e^{T_1 \left(\frac{\lambda(p-d)}{2d}(-2+\theta T_1) + \frac{\lambda p}{d} + \mu \right)} - e^{T_1 \left(\frac{T_1 p \theta}{2d} + 1 - \frac{\theta T_1}{2} \right)}}{e^{T_1 \left(\frac{\lambda p}{d} + \mu \right)}}}. \quad (32)$$

The derivative of (32) with respect to T_1 is:

$$\frac{dTCT(T_1)}{dT_1} = \frac{(M\mu e^{-\mu T_1} + (h\frac{p}{d} + \pi\theta)(h(p-d)T_1 e^{-\mu T_1})) \left(e^{T_1(\frac{\lambda p}{d} + \mu)} \right) - Sd \left(\lambda \left(\frac{T_1 p \theta}{d} + 1 - \theta T_1 + \frac{p}{d} + \frac{\mu}{\lambda} \right) A_e + \left(\frac{\lambda(d-p)}{d} + \frac{(p-d)\lambda\theta T_1}{d} \right) B_e \right)}{\left(\frac{p(1-e^{-(\mu T_1)})}{d\mu} \right) \left(e^{T_1(\frac{\lambda p}{d} + \mu)} \right) - A_e + B_e},$$

$$\frac{\left(\left(K + M(1 - \mu e^{-\mu T_1}) + (h\frac{p}{d} + \pi\theta) \left(\frac{(p-d)(1-e^{-\mu T_1} - \mu T_1 e^{-\mu T_1})}{\mu^2} \right) \right) \left(e^{T_1(\frac{\lambda p}{d} + \mu)} \right) - \frac{Sde^{-\frac{\lambda p}{d} - d\theta T_1}}{\lambda} \right) Ce}{\left(\left(\frac{p(1-e^{-(\mu T_1)})}{d\mu} \right) \left(e^{T_1(\frac{\lambda p}{d} + \mu)} \right) - A_e + B_e \right)^2},$$

(33)

where:

$$A_e = e^{T_1 \left(\frac{T_1 p \theta}{d} + 1 - 0.5\theta T_1 \right)},$$

$$B_e = e^{T_1 \left(\frac{\lambda(d-p)}{d} + \frac{(p-d)\lambda\theta T_1}{d} + \frac{\lambda p}{d} + \mu \right)},$$

$$C_e = \frac{p e^{-\mu T_1}}{d} - \frac{\lambda \left(\frac{T_1 p \theta}{d} + 1 - 0.5\theta T_1 - \frac{p}{d} - \frac{\mu}{\lambda} \right) e^{A_e} + \left(\frac{\lambda(d-p)}{d} + \frac{(p-d)\lambda\theta T_1}{d} \right) e^{B_e}}{\left(e^{T_1(\frac{\lambda p}{d} + \mu)} \right)},$$

The optimal T_1 can be derived by equating (33) to zero. The optimal T_1 can be solved using a simple line search method since the total cost function is convex for small value of λ , μ , and T_1 under these conditions:

$$\lambda < \frac{(d\mu + p)}{2(p-d)}$$

and

$$M < \frac{\left(h\frac{p}{d} + \pi\theta \right) (p-d) - Sd \left(2 \left(\frac{\lambda\mu(p-d)}{d} \right) - \mu^2 \right)}{\mu^2}.$$

The detailed calculation is shown in Appendix B.

3. Example and sensitivity analysis

Similar data as Lin and Gong [29] is used to illustrate the uniform distribution repair time model and to compare the model with the fixed repair time model. In the comparison, the uniform distribution repair time mean rate is equal to the fixed repair time. Considering $K = \$50$ per production cycle, $M = \$200$ per repair, $p = 10,000$ units per unit time, $d = 7500$ units per unit time, $h = \$1$ per unit per unit time, $S = \$5$ per unit, $\theta = 0.2$, unavailability time is uniformly distributed over the interval $[0, 0.7]$, $\mu = 0.2$ and the fixed repair time equals to 0.05. Here, Maple 8 is used to solve (29) resulting in $T_1 = 0.202$. The optimal total cost per unit time can be found by substituting T_1 in (28) resulting in $TCT = \$640.8$. In the study, the performance of the stochastic repair time with the fixed repair time for different lost sales and repair times is compared. Fig. 2 shows the optimal production period. The figure shows that the production time of the stochastic model is shorter than the fix model for small lost sales cost and longer for high lost sales cost. The optimal production time of the stochastic model is more sensitive to the lost sales costs. Fig. 3 shows the total cost of the stochastic model and the fix model for different lost sales costs.

Fig. 4 shows the production period of the stochastic model and the fix model for different repair times. The figure shows that the optimal production time of the stochastic model is less sensitive in varying repair time than the fix model. Also, the figure shows that the optimal production time difference between the stochastic model and the fix model is wider when the repair time is increased. Fig. 5 shows the total cost of the stochastic model and the fix model for varying repair time.

The sensitivity analysis of the stochastic repair model with exponential distribution repair time uses similar data as the uniform distribution repair time model except that the maintenance rate (λ) equals to 20 is used. The sensitivity analysis is conducted by varying the data from -20% to 20% .

Fig. 6 shows that the production rate is the most important parameter in decision making since it is the most sensitive parameter of the optimal production time.

Fig. 7 shows the sensitivity analysis of the total cost per unit time for various parameter values; the total cost is sensitive to the change in production rate, demand rate, holding cost and repair time rate. The total cost tends to increase as the parameter values increase except for repair time and production rate.

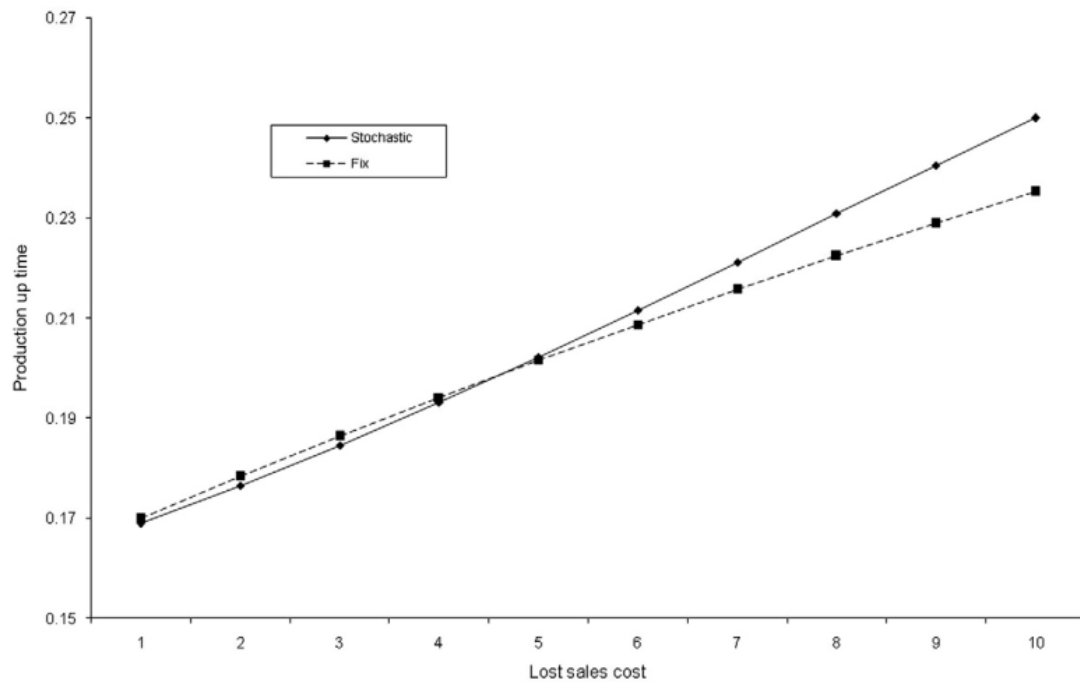


Fig. 2. Comparison of T_1 for different lost sales cost.

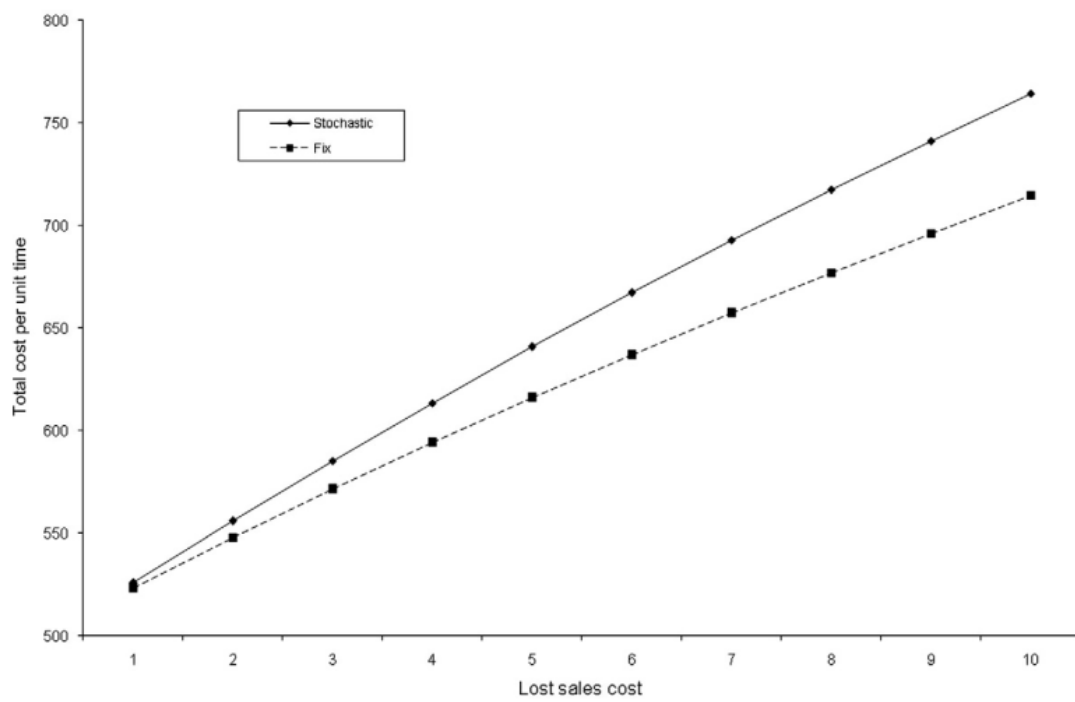


Fig. 3. Comparison of the total cost for different lost sales.

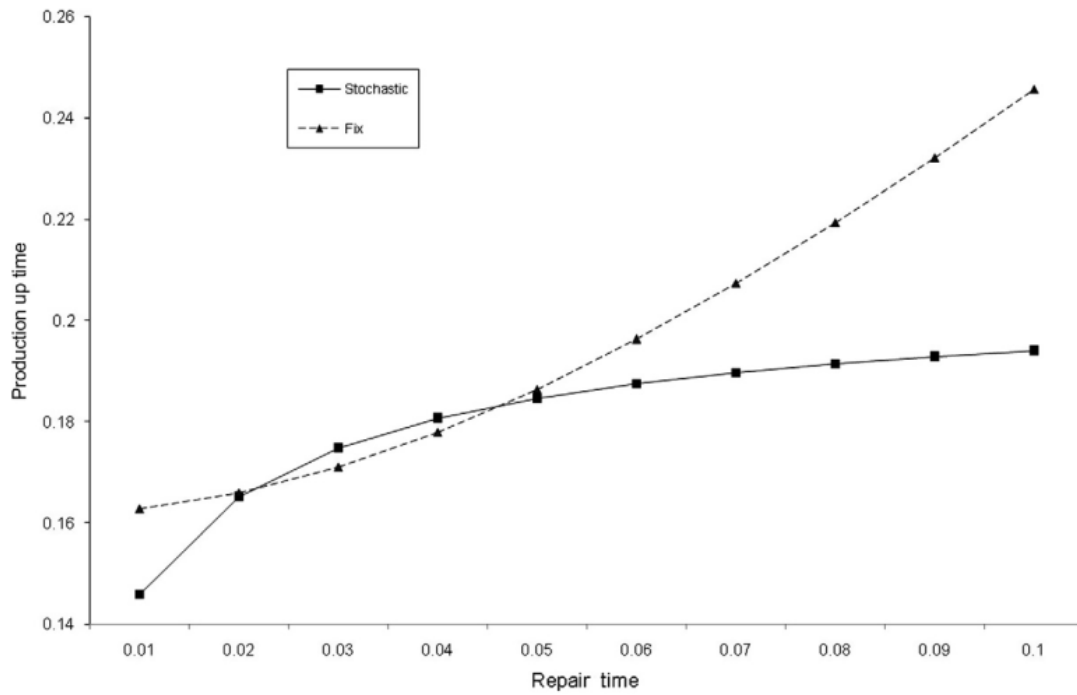


Fig. 4. Comparison of T_1 for different repair times.

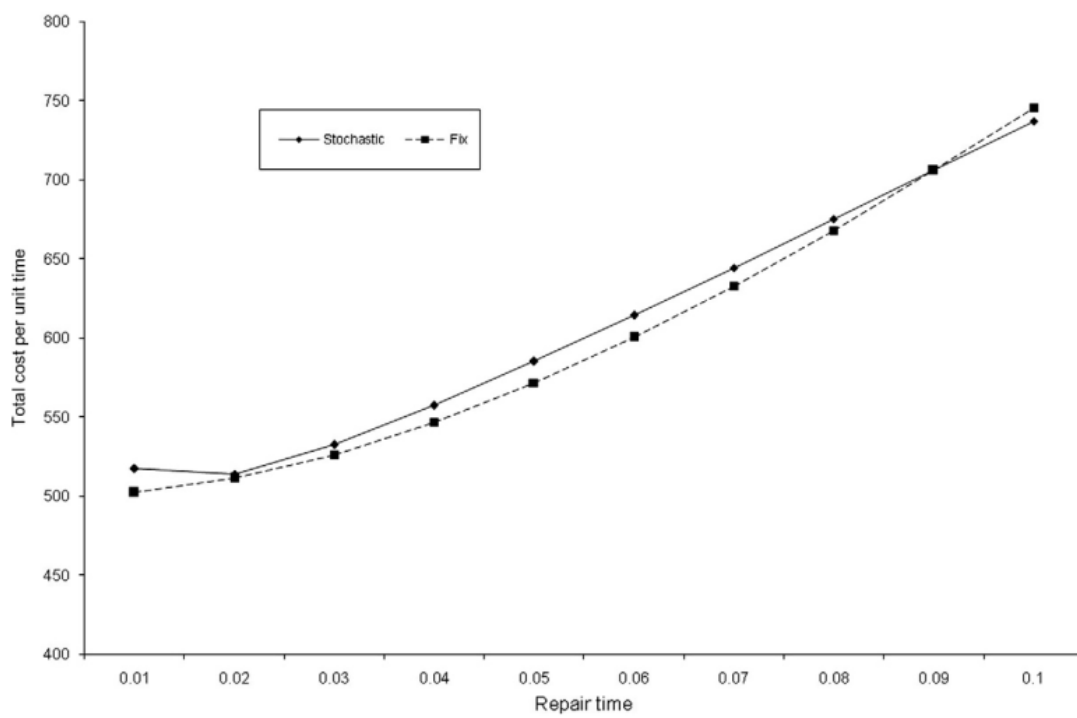


Fig. 5. Comparison of the total cost for different repair times.

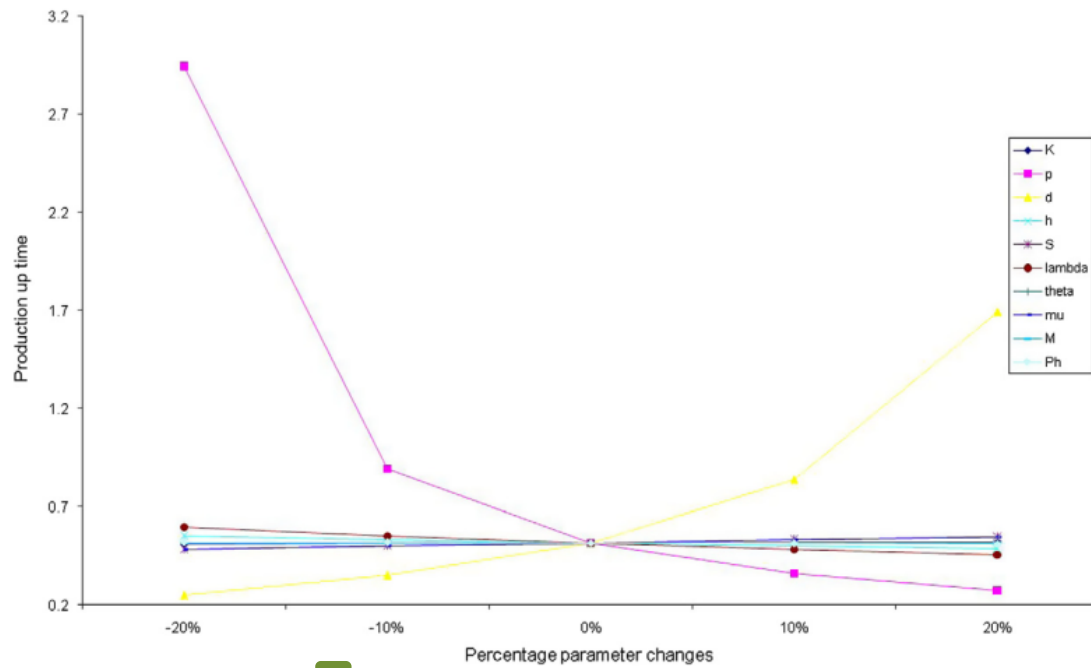


Fig. 6. Sensitivity analysis of T_1 for the exponential distribution model.

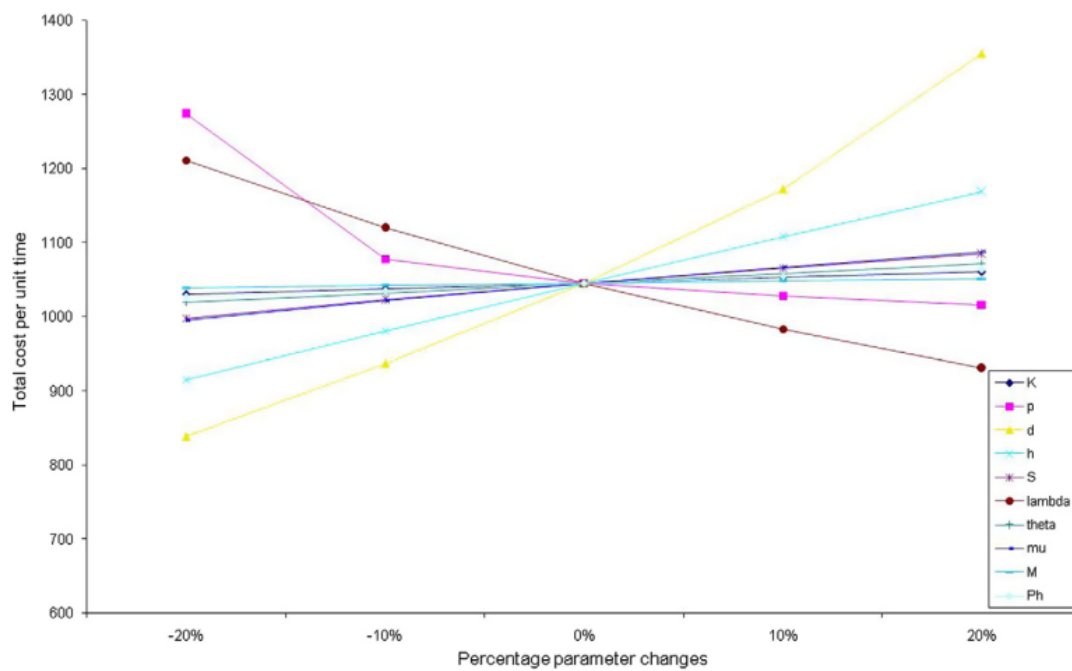


Fig. 7. Sensitivity analysis of the total cost per unit time for the exponential distribution model.

4. Conclusion

The deteriorating items production inventory models with machine breakdown and stochastic repair time (for uniformly and exponentially distributed repair time) have been developed. The sensitivity analysis support a management concept that

management of [5] to set longer production up time in the stochastic repair time environment than the fixed time repair time, especially when the lost sales cost is high. The total cost difference between the stochastic model and the fix model is wider when lost sale cost increases. Therefore, it is very critical for management to assume stochastic repair time when the lost sales cost is high. When the repair time varies, the optimal production time of the stochastic model is less sensitive than the fix model and the total cost gap is also smaller for varying lost sales cost. Management should give more attention to the production rate since the production rate and the demand rate (which is not easily controlled) are the most sensitive parameters to the total cost for the exponentially distributed repair time model. The sensitivity analysis supports management concept that higher machine probability breakdown and longer machine repair time result in a higher total cost. The results from the study can give meaningful management insights in production planning and control. Future research can be done to consider preventive maintenance and normal distribution corrective time.

Appendix A

Using Property 1, we set $f(x)$ = the total cost per unit time, $g(x)$ = the total cost and $h(x)$ = the total replenishment time. The total cost per unit time is convex if the total cost is convex and the total replenishment time is concave. The total cost of uniform distribution repair time is:

$$TC_U = K + M(1 - e^{-\mu T_1}) + h \frac{p(p-d)(1 - e^{-\mu T_1} - \mu T_1 e^{-\mu T_1})}{\mu^2 d} + \pi \theta \frac{(p-d)\theta(1 - e^{-\mu T_1} - \mu T_1 e^{-\mu T_1})}{\mu^2} + Sd \left(\frac{((b\mu d)^2 - 2b(p-d)\mu d + (p-d)^2)(1 - e^{-\mu T_1}) - e^{-\mu T_1} \mu T_1 (p-d)((p-d)(2 + \mu T_1) - 2b\mu d)}{2b\mu^2 d^2} \right). \quad (A1)$$

The second derivative of (A1) with respect to T_1 is:

$$\frac{d^2 TC_U}{dT_1^2} = -M\mu^2 e^{-\mu T_1} + \left(\frac{hp}{d} + \pi\theta \right) ((p-d)(1 - b\mu)e^{-\mu T_1}) - S \left(\frac{(e^{-\mu T_1})\mu^4 (bd(bd + 2T_1(d-p) + T_1^2(p-d)^2) + 2e^{-\mu T_1})\mu^3 (bd(p-d) - 2T_1((p-d)^2))}{2db\mu^2} \right). \quad (A2)$$

Set $T_1 = 0$, one has:

$$\frac{d^2 TC_U}{dT_1^2} = -M\mu^2 + (p-d) \left(\frac{hp}{d} + \pi\theta \right) - \frac{S\mu bd(\mu bd + 2(p-d))}{2}. \quad (A3)$$

Eq. (A3) is convex if:

$$M < \frac{(p-d) \left(\frac{hp}{d} + \pi\theta \right) - \frac{S\mu bd(\mu bd + 2(p-d))}{2}}{\mu^2}. \quad (A4)$$

Set $T_1 = \frac{db(1-\frac{\theta}{p-d})}{\mu}$, one has:

$$\frac{d^2 TC_U}{dT_1^2} = \frac{1}{d} (h(8p(p-d) - 4pb\mu d(2 + b\theta)) - S(4\mu bd\theta(p-d) + b(\mu bd\theta)^2) + \pi(4\theta d(2p - 2d - 2p\delta b\mu - \mu^2 d\theta))) - M\mu^2 d e^{\left(\frac{\mu db(2 + b\theta)}{2(p-d)} \right)}. \quad (A5)$$

Eq. (A5) convex if:

$$M < \frac{(hp + \pi d\theta)(8(p-d) - 4b\mu d(2 + b\theta)) - S\mu bd\theta(4(p-d) + \mu b^2 d\theta)}{\mu^2 d}. \quad (A6)$$

The total cost of uniform distribution repair time is convex in $0 \leq T_1 \leq \frac{db(1-\frac{\theta}{p-d})}{\mu}$ when (A4) and (A6) are fulfilled. The expected replenishment time of uniform distribution repair can be written as follows:

$$E(T) = \frac{p(1 - e^{-\mu T_1})}{d\mu} + Sd \left(\frac{((b\mu d)^2 - 2b(p-d)\mu d + (p-d)^2)(1 - e^{-\mu T_1}) - e^{-\mu T_1} \mu T_1 (p-d)((p-d)(2 + \mu T_1) - 2b\mu d)}{2b\mu^2 d^2} \right). \quad (A7)$$

The second derivative of (A7) with respect to T_1 is:

$$\frac{dT_C}{dT_1} = \frac{p\mu e^{-\mu T_1}}{d} - S \left(\frac{(e^{-\mu T_1})\mu^4(bd(bd + 2T_1(d-p) + T_1^2(p-d)^2) + 2(e^{-\mu T_1})\mu^3(bd(p-d) - 2T_1((p-d)^2)))}{2db\mu^2} \right). \quad (A8)$$

Set $T_1 = 0$, one has:

$$\frac{dT_U^2}{dT_1} = -\frac{\mu(2(p-d) + 2p + \mu bd)}{2d}. \quad (A9)$$

Eq. (A9) is concave since $d < p$.

Set $T_1 = \frac{db(1-\frac{\theta b}{2})}{p-d}$, one has:

$$\frac{dT_U^2}{dT_1} = -\frac{(4p(2-\theta b) + \theta bd(4 + b^2\mu\theta))\mu e^{\left(\frac{-\mu bd(2+\theta b)}{2(p-d)}\right)}}{8d}. \quad (A10)$$

Eq. (A10) is concave if: $\theta b < 2$. So the expected total time of uniform distribution repair time is concave in $0 \leq T_1 \leq \frac{db(1-\frac{\theta b}{2})}{p-d}$ if $\theta b < 2$.

Appendix B

The expected replenishment time of exponential distribution repair time can be written as follows:

$$E(T_E) = \frac{p(1 - e^{-\mu T_1})}{d\mu} + \left(\frac{-e^{T_1(0.5\theta T_1(\frac{p-d}{d})+1)} + e^{T_1(0.5\theta T_1(\frac{p-d}{d})+1+\frac{\mu}{\lambda})}}{e^{T_1(\frac{\lambda p}{d}+\mu)}} \right). \quad (B1)$$

The second derivative of (B1) with respect to T_1 is:

$$\begin{aligned} \frac{dT_E^2}{dT_1} = & \left(-\lambda \left(\theta \frac{(p-d)}{d} \right) e^{T_1(0.5\theta T_1(\frac{p-d}{d})+\lambda)} - \left(\theta T_1 \lambda \left(\frac{p-d}{d} \right) + \lambda \right)^2 e^{T_1(0.5\theta T_1(\frac{p-d}{d})+\lambda)} + \frac{(p-d)}{d} \lambda \theta e^{T_1(0.5\theta T_1(\frac{p-d}{d})+\lambda+\mu)} \right. \\ & + \left(\theta T_1 \lambda \left(\frac{p-d}{d} \right) + \lambda + \mu \right)^2 e^{T_1(0.5\theta T_1(\frac{p-d}{d})+\lambda+\mu)} \frac{1}{e^{T_1(\frac{\lambda p}{d}+\mu)}} - 2 \left(- \left(\theta T_1 \lambda \left(\frac{p-d}{d} \right) + \lambda \right) e^{T_1(0.5\theta T_1(\frac{p-d}{d})+\lambda)} \right. \\ & \left. \left. + \left(\theta T_1 \lambda \left(\frac{p-d}{d} \right) + \lambda + \mu \right) e^{T_1(0.5\theta T_1(\frac{p-d}{d})+\lambda+\mu)} \right) \frac{(\frac{\lambda p}{d} + \mu)}{e^{T_1(\frac{\lambda p}{d}+\mu)}} + \left(-e^{T_1(0.5\theta T_1(\frac{p-d}{d})+\lambda)} + e^{T_1(0.5\theta T_1(\frac{p-d}{d})+\lambda+\mu)} \right) \frac{(\frac{\lambda p}{d} + \mu)^2}{e^{T_1(\frac{\lambda p}{d}+\mu)}} \right) < 0. \quad (B2) \end{aligned}$$

Eq. (B2) can be simplified as:

$$\begin{aligned} \frac{dT_E^2}{dT_1} = & -\frac{p\mu e^{-\mu T_1}}{d} + \left(-\lambda \left(\theta \frac{(p-d)}{d} \right) Z - \left(\theta T_1 \lambda \left(\frac{p-d}{d} \right) + \lambda \right)^2 Z + \frac{(p-d)}{d} \lambda \theta Z e^{\mu T_1} \right. \\ & + \left(\theta T_1 \lambda \left(\frac{p-d}{d} \right) + \lambda + \mu \right)^2 Z e^{\mu T_1} \frac{1}{e^{T_1(\frac{\lambda p}{d}+\mu)}} - 2 \left(- \left(\theta T_1 \lambda \left(\frac{p-d}{d} \right) + \lambda \right) Z + \left(\theta T_1 \lambda \left(\frac{p-d}{d} \right) + \lambda + \mu \right) Z e^{\mu T_1} \right) \frac{(\frac{\lambda p}{d} + \mu)}{e^{T_1(\frac{\lambda p}{d}+\mu)}} \\ & \left. + (-Z + Z e^{\mu T_1}) \frac{(\frac{\lambda p}{d} + \mu)^2}{e^{T_1(\frac{\lambda p}{d}+\mu)}} < 0, \quad (B3) \end{aligned}$$

where:

$$Z = e^{T_1(0.5\theta T_1(\frac{p-d}{d})+\lambda)}.$$

We can rewrite (B3) as:

$$\frac{dT_E^2}{dT_1} = dT_{E1} + dT_{E2},$$

where:

$$dT_{E1} = -\frac{p\mu e^{-\mu T_1}}{d} \quad (B4)$$

and

$$\begin{aligned} dT_{E2} = & \left(\lambda \left(\theta \frac{(p-d)}{d} \right) (-1 + e^{\mu T_1}) - \left(\theta T_1 \lambda \left(\frac{p-d}{d} \right) + \lambda \right)^2 Z + \left(\theta T_1 \lambda \left(\frac{p-d}{d} \right) + \lambda + \mu \right)^2 Z e^{\mu T_1} \right) \\ & + 2 \left(\left(\theta T_1 \lambda \left(\frac{p-d}{d} \right) + \lambda \right) Z - \left(\theta T_1 \lambda \left(\frac{p-d}{d} \right) + \lambda + \mu \right) Z e^{\mu T_1} \right) \frac{(\frac{\lambda p}{d} + \mu)}{e^{T_1(\frac{\lambda p}{d}+\mu)}} + (-Z + Z e^{\mu T_1}) \left(\frac{\lambda p}{d} + \mu \right)^2. \quad (B5) \end{aligned}$$

Eq. (B5) can be rewritten as:

$$dT_{E2} = \lambda \left(\theta \frac{(p-d)}{d} \right) (-1 + e^{\mu T_1}) - (Z_a - C)^2 Z + (Z_b - C)^2 Z e^{\mu T_1}, \quad (B6)$$

where:

$$\begin{aligned} Z_a &= \theta T_1 \lambda \left(\frac{p-d}{d} \right) + \lambda, \\ Z_b &= \theta T_1 \lambda \left(\frac{p-d}{d} \right) + \lambda + \mu, \\ C &= \left(\frac{\lambda p}{d} + \mu \right). \end{aligned}$$

Since $Z_b > Z_a$ then (B6) is positive, so the expected total time of exponential distribution repair time is concave if:

$$\frac{p\mu e^{-\mu T_1}}{d} > \lambda \left(\theta \frac{(p-d)}{d} \right) (-1 + e^{\mu T_1}) - (Z_a - C)^2 Z + (Z_b - C)^2 Z e^{\mu T_1}. \quad (B7)$$

When θT_1 is small (B7) can be rewritten as:

$$\frac{p\mu e^{-\mu T_1}}{d} > \lambda \left(\theta \frac{(p-d)}{d} \right) (-1 + e^{\mu T_1}) - (\lambda - C)^2 e^{\lambda T_1} + (\lambda + \mu - C)^2 e^{(\lambda + \mu) T_1}. \quad (B8)$$

When λ , μ , and T_1 are small, and through some simplifications one has:

$$2 \left(\frac{p(\lambda - 0.5) - \lambda d}{d} \right) - \mu < 0. \quad (B9)$$

Eq. (B9) true if $\lambda < 0.5$ or $\lambda < \frac{d\mu + p}{2(p-d)}$. So the expected time for exponential distribution time is also concave when λ , μ , and T_1 are small and $\lambda < 0.5$ or $\lambda < \frac{d\mu + p}{2(p-d)}$.

The total cost model of exponential distribution repair time can be modeled as:

$$\begin{aligned} TC_E &= K + M(1 - e^{-\mu T_1}) + h \frac{p(p-d)(1 - e^{-\mu T_1} - \mu T_1 e^{-\mu T_1})}{\mu^2 d} + \pi \theta \frac{(p-d)(1 - e^{-\mu T_1} - \mu T_1 e^{-\mu T_1})}{\mu^2} \\ &+ Sd \left(\frac{-e^{\lambda T_1 (0.5\theta T_1 (\frac{p-d}{d}) + 1)} + e^{\lambda T_1 (0.5\theta T_1 (\frac{p-d}{d}) + 1 + \frac{\mu}{\lambda})}}{e^{T_1 (\frac{\lambda p}{d} + \mu)}} \right). \end{aligned} \quad (B10)$$

The second derivative of (B10) with respect to T_1 is:

$$\begin{aligned} \frac{d^2 TC_E}{dT_1^2} &= -M\mu^2 e^{-\mu T_1} + \left(\frac{hp}{d} + \pi \theta \right) (p-d) e^{-\mu T_1} (1 - \mu T_1) + Sd \left(\left(-\lambda \left(\theta \frac{(p-d)}{d} \right) e^{T_1 (0.5\theta T_1 (\frac{p-d}{d}) + \lambda)} \right. \right. \\ &- \left(\theta T_1 \lambda \left(\frac{p-d}{d} \right) + \lambda + \mu \right)^2 e^{T_1 (0.5\theta T_1 (\frac{p-d}{d}) + \lambda)} + \frac{(p-d)}{d} \lambda \theta e^{T_1 (0.5\theta T_1 (\frac{p-d}{d}) + \lambda + \mu)} \\ &+ \left(\theta T_1 \lambda \left(\frac{p-d}{d} \right) + \lambda + \mu \right)^2 e^{T_1 (0.5\theta T_1 (\frac{p-d}{d}) + \lambda + \mu)} \left. \right) \frac{1}{e^{T_1 (\frac{\lambda p}{d} + \mu)}} - 2 \left(-\left(\theta T_1 \lambda \left(\frac{p-d}{d} \right) + \lambda \right) e^{T_1 (0.5\theta T_1 (\frac{p-d}{d}) + \lambda)} \right. \\ &+ \left. \left(\theta T_1 \lambda \left(\frac{p-d}{d} \right) + \lambda + \mu \right) e^{T_1 (0.5\theta T_1 (\frac{p-d}{d}) + \lambda + \mu)} \right) \frac{(\frac{\lambda p}{d} + \mu)}{e^{T_1 (\frac{\lambda p}{d} + \mu)}} + \left(-e^{T_1 (0.5\theta T_1 (\frac{p-d}{d}) + \lambda)} + e^{T_1 (0.5\theta T_1 (\frac{p-d}{d}) + \lambda + \mu)} \right) \frac{(\frac{\lambda p}{d} + \mu)^2}{e^{T_1 (\frac{\lambda p}{d} + \mu)}} \right). \end{aligned} \quad (B11)$$

When λ , μ , and T_1 are small, (B11) can be rewritten as:

$$\frac{d^2 TC_E}{dT_1^2} = -M\mu^2 + \left(\frac{hp}{d} + \pi \theta \right) (p-d) - Sd \left(\left(\lambda - \left(\frac{\lambda p}{d} + \mu \right) \right)^2 + \left(\lambda + \mu - \left(\frac{\lambda p}{d} + \mu \right) \right)^2 \right) > 0.$$

The expected total cost of exponential distribution repair time is convex if:

$$M < \frac{\left(\frac{hp}{d} + \pi \theta \right) (p-d) - Sd \left(2 \left(\frac{\lambda \mu (p-d)}{d} \right) - \mu^2 \right)}{\mu^2}. \quad (B12)$$

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