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An Imperfect Production System with Predictive Maintenance Policy under Trade Credit

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Abstract

This paper develops an economic production quantity (EPQ) model considering predictive maintenance and trade credit with an imperfect production process. Predictive maintenance, with the help of sensors and data analysis, can execute maintenance before the system becomes out of control and can improve system reliability. We also consider a trade credit policy that allows manufacturers to delay their payments. Based on the relationships among production runtime, inventory cycle time, and credit period, we divide the model into three cases. The objective is to determine the optimal production runtime and predictive maintenance effort to maximize the total expected profit. We develop a piecewise nonlinear optimization algorithm to solve the problems described. Based on numerical experiments, we discuss the influences of system parameters on decisions and profit. The results of this study can serve as references for business managers and administrators.

Keywords: Inventory, imperfect production system, predictive maintenance, corrective maintenance, trade credit.

1. Introduction

With the help of Industry 4.0, predictive maintenance can improve production systems through sensor adoption, advanced monitoring, and forecasting techniques that can reduce the difference between imperfect and perfect production systems. Predictive maintenance is a new strategy to perform maintenance before control is lost (or system breakdown). A predictive maintenance can be subdivided into three stages: (1) the characterize and measurement of maintenance needs, (2) ordering of the needed items, and (3) formulation of a predictive maintenance procedure (see Terence [19]). Predictive maintenance is used extensively for monitoring the conditions of various machines (see Wen et al. [23]). This policy could successfully be applied to a production system when it breaks down or is in an out-of-control state (produces more imperfect items).

However, there is little research considering the economic-production-quantity (EPQ) model with predictive and corrective maintenance policies. Most EPQ research considered preventive, corrective, and maintenance policies. Ben-Daya and Makhdoum [2] investigated the effect of various preventive maintenance policies on the joint optimization of the economic production quantity (EPQ) and the economic design of the control chart. Ben-Daya [1] developed a model that links EPQ, quality, and maintenance requirements for a process having a general deterioration distribution and where the maintenance level is optimized. Jamal et al. [8] proposed an EPQ model in which defective products from each production cycle are accumulated until N equal cycles. Pal et al. [13] dealt with an EPQ model in an imperfect production system. Taleizadeh et al. [16] presented an EPQ inventory model with an interruption in process, scrap, and rework. Sarkar et al. [14] considered an EPQ model with a random defective rate and rework process for a single-stage manufacturing system with planned backorders. Wen et al. [23] integrated predictive maintenance in an EPQ model in which an autoregressive integrated-moving-average model was adopted to predict a system's health. Huang et al. [7] presented an EPQ model with an imperfect production process and corrective maintenance. They focused on examining an imperfect production system with shortages. Sett et al. [15] considered the optimal buffer inventory and inspection policy for an imperfect production system with preventive maintenance. In a different way, we consider the predictive maintenance effort as one of our decision variables. The objective is to determine the optimal predictive maintenance effort and production runtime to maximize the total expected profit.

Another policy that should be considered in an EPQ model is trade credit. Trade credit enables customers to delay their payments. Goyal [5] first proposed an economic order quantity model that enables suppliers to allow customers to delay their payments. Chung and Huang [4] extended Goyal's [5] model to a case for which the units are replenished at a finite rate. Huang [6] modeled a retailer's inventory system to investigate the optimal retailer's replenishment decisions under two levels of trade credit policy within the EPQ framework. Teng and Chang [18] extended Huang's [6] EPQ model to complement the shortcomings of the model. Recently, Tsao et al. [20] demonstrated an EPQ model by considering the reworking of imperfect items and trade credit. Kreng and Tan [9] proposed an EPQ model to determine the optimal replenishment decision with an imperfect-quality product under a supply chain trade credit policy. Chen et al. [3] presented economic production quantity models developed for deteriorating items under conditions of upstream full-trade credit and downstream partial-trade credit. Tsao et al. [21] proposed an imperfect production quantity to determine the maintenance frequency under trade credit conditions. Tayal et al. [17] developed an integrated production inventory model for perishable products with a trade credit period and investment in preservation technology. Tsao et al. [22] developed an EPQ model based on radio frequency identification adoption, trade credit policy, and reworking of imperfect products. However, all these trade credit studies considered corrective maintenance or preventive maintenance. We consider both predictive maintenance and corrective maintenance to adapt to the era of Industry 4.0.

Because trade credit is a widespread and popular payment method in modern business and predictive maintenance activity is important in an intelligent production system, thus, in order to respond to the real business behavior, we consider predictive maintenance and trade credit in modeling production systems in the Industry 4.0 era. This paper contributes to the literature and to practice are as follows. First, this is the first study to incorporate the predictive maintenance decision into the imperfect production system under process deterioration and trade credit. In our model, we assumed that the production system may shift from an in-control to an out-of-control state, causing a higher defective rate. Predictive maintenance is conducted to improve system reliability, and corrective maintenance is executed when the production system is at the out-of-control state. Second, we also propose an algorithm to solve the three-branch piecewise nonlinear problem and obtain the optimal production runtime and predictive maintenance efforts. Finally, a numerical analysis is conducted for determining the effects of changing parameters, and management implications are provided.

The remainder of this work is organized as follows. In Section 2, we describe the assumptions, the notation, and the mathematical model. An approach to the solution is proposed in Section 3. In Section 4, we present the numerical analysis. Finally, in Section 5, some conclusions are drawn, and future research is discussed.

2. Model Formulation

In this model, we mainly formulate the EPQ model to determine the optimal predictive effort and the production run time while maximizing the expected profit. The supplier provides the manufacturer a permissible delay in payments (trade credit) and the manufacturers could sell the goods and accumulate revenue and earn interest within the trade credit period. Both of interests charged and earned are calculated based on time in our EPQ model to maximize the manufacturer's profit. In the EPQ model, a constant production rate starts at $t = 0$, and continues up to $t = T_p$ where the inventory level reaches the maximum level. Production then stops at $t = T_p$; at the beginning of the production process, the system is in an in-control state, and it is possible for the system to shift to an out-of-control state as time goes by while the system continues to produce products (Figure 1). Suppose the manufacturer puts effort for predictive maintenance into the production system and makes decisions on its predictive maintenance effort ρ and production runtime T_p.

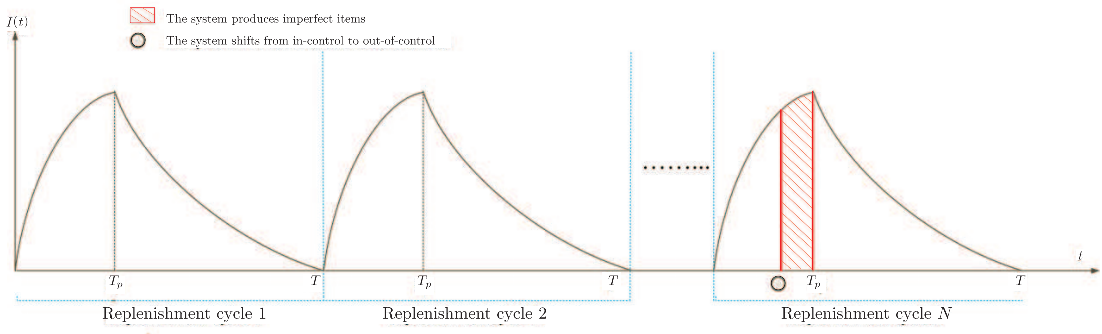

Figure 1: Replenishment cycle of imperfect EPQ model with perfect repair and rework.

This study uses the following notation.

Decision variables:

ε	Predictive maintenance efforts.
T_p	Length of production runtime.

Parameters:

P	Production rate per unit time.
d_1	Demand rate of perfect items per unit time.
d_2	Demand rate of imperfect items per unit time.
d	Total remand rate per unit time, $d = d_1 + d_2$.
M	Trade credit period (unit time).
T	Inventory cycle time (unit time), $T = \dfrac{PT_p}{d_1 + d_2}$.
I_e	Rate of interest earned $0 \le I_e \le 1$.
I_P	Rate of interest charged $0 \le I_P \le 1$.
τ	The production time until the system shift began to be out of control (unit time).
S_1	Selling price of perfect quality per item ($S_1 > C_m$).
S_2	Selling price of defective quality per item ($S_2 > C_m$).
C_S	Setup cost per unit time.
h	Inventory cost per unit per unit time.
C_{insp}	Inspection cost per unit.
C_m	Manufacturing cost per unit.
C_{CM}	Corrective maintenance cost per time.
C_{PdM}	Predictive maintenance cost per time.
a_{in}	Defective rate when the system is in control.
a_{out}	Defective rate when the system is out of control.
γ, η	The coefficient of failure rate function with respect to preventive maintenance effort ($\gamma > 0$ and $\eta > 0$).
λ	The number of crashes.

The mathematical model is developed under the following assumptions:

a. τ is a random variable that is also the time from the beginning to the time when the system is out of control. τ is assumed to be exponentially distributed with a mean of λ^{-1}. A similar assumption can be seen in Lee and Rosenblatt [10].
b. The relationship between the number of crashes and predictive maintenance efforts is negative and satisfies $\lambda = \gamma + \eta e^{-\varepsilon}$ (where $\gamma > 0$ and $\eta > 0$). The higher predictive maintenance effort decreases the number of crashes (see Mobley [11]).
c. The supplier provides the manufacturer a permissible delay in payments. During credit period the account is not settled, generated sales revenue is deposited in an interest-bearing account with interest rate I_e. At the end of the permissible delay, the manufacturer pays off all units ordered and starts paying for the interest charges on the raw material in stocks with interest rate I_P. A similar assumption can be seen in Ouyang and Chang [12]; Kreng and Tan [9]; Tayal et al. [17], etc. The interest earned and charges of manufactures are also calculated based on the perfect- and imperfect-items sale revenues in each period.
d. Selling price of defective quality items is lower than selling price of perfect quality items ($S_2 < S_1$).
e. The production operation starts at time 0, and system status is in control.
f. Production length is fixed for each round.
g. System will keep on producing items in out-of-control status with defective rate a_{out}.
h. Corrective maintenance cannot be executed during system operation.

In our model, the components of the mathematical model are calculated as follows:

• **The annual revenue**

(1) *Annual perfect-item sale revenue*

Let Y be the number of perfect items in each production cycle

$$Y = \begin{cases} (1-a_{\text{in}})PT_P, & \text{if } \tau \geq T_P, \\ (1-a_{\text{in}})P\tau + (1-a_{\text{out}})P(T_P-\tau), & \text{if } \tau < T_P. \end{cases} \tag{2.1}$$

Then, the expected number Y for every production cycle is

$$\begin{aligned} E(Y) &= \int_{T_P}^{\infty} (1-a_{\text{in}})PT_P\lambda e^{-\lambda\tau}d\tau + \int_0^{T_P} [(1-a_{\text{in}})P\tau + (1-a_{\text{out}})P(T_P-\tau)]\lambda e^{-\lambda\tau}d\tau \\ &= -P(1-a_{\text{in}})\frac{e^{-\lambda T_P}-1}{\lambda} + P(1-a_{\text{out}})\Big(T_P + \frac{e^{-\lambda T_P}-1}{\lambda}\Big). \end{aligned} \tag{2.2}$$

The annual sale revenue from perfect items is

$$\frac{S_1E(Y)}{T} = \frac{S_1E(Y)}{PT_P}(d_1+d_2)$$

$$=S_1(d_1+d_2)\Big[-(1-a_{\text{in}})\frac{e^{-\lambda T_P}-1}{\lambda T_P}+(1-a_{\text{out}})\Big(1+\frac{e^{-\lambda T_P}-1}{\lambda T_P}\Big)\Big]. \quad (2.3)$$

McClaurin series are used to approximate $e^{-\lambda T_P}\approx 1-\lambda T_P+\dfrac{(\lambda T_P)^2}{2}$. Thus, we can rewrite the annual perfect-item revenue as

$$\begin{aligned}\frac{S_1E(Y)}{T}&=\frac{S_1E(Y)}{PT_P}(d_1+d_2)\approx\frac{1}{2}S_1(d_1+d_2)(2-\lambda T_P a_{\text{out}}+a_{\text{in}}(-2+\lambda T_P))\\&=\frac{1}{2}S_1(d_1+d_2)\Big(2-(\gamma+\eta e^{-\varepsilon})T_P a_{\text{out}}+a_{\text{in}}(-2+(\gamma+\eta e^{-\varepsilon})T_P)\Big). \quad (2.4)\end{aligned}$$

(2) *Annual imperfect-item sale revenue*

Let N be the number of imperfect items in each production cycle

$$N=\begin{cases}a_{\text{in}}PT_P, & \text{if } \tau\ge T_P,\\ a_{\text{in}}P\tau+a_{\text{out}}P(T_P-\tau), & \text{if } \tau<T_P.\end{cases} \quad (2.5)$$

Then, the expected number N for every production cycle is

$$\begin{aligned}E(N)&=\int_{T_P}^{\infty}a_{\text{in}}PT_P\lambda e^{-\lambda\tau}d\tau+\int_0^{T_P}[a_{\text{in}}P\tau+a_{\text{out}}P(T_P-\tau)]\lambda e^{-\lambda\tau}d\tau\\&=-Pa_{\text{in}}\frac{e^{-\lambda T_P}-1}{\lambda}+Pa_{\text{out}}\Big(T_P+\frac{e^{-\lambda T_P}-1}{\lambda}\Big). \quad (2.6)\end{aligned}$$

The annual sale revenue from imperfect items is

$$\begin{aligned}\frac{S_2E(Y)}{T}&=\frac{S_2E(Y)}{PT_P}(d_1+d_2)\\&=S_2(d_1+d_2)\Big[-a_{\text{in}}\frac{e^{-\lambda T_P}-1}{\lambda T_P}+a_{\text{out}}\Big(1+\frac{e^{-\lambda T_P}-1}{\lambda T_P}\Big)\Big]. \quad (2.7)\end{aligned}$$

Using McClaurin series, we can rewrite the annual imperfect-item revenue as

$$\begin{aligned}\frac{S_2E(Y)}{T}&\approx\frac{1}{2}(d_1+d_2)S_2[a_{\text{out}}\lambda T_P+a_{\text{in}}(2-\lambda T_P)]\\&=\frac{1}{2}(d_1+d_2)S_2\Big[a_{\text{out}}(\gamma+\eta e^{-\varepsilon})T_P+a_{\text{in}}(2-(\gamma+\eta e^{-\varepsilon})T_P)\Big]. \quad (2.8)\end{aligned}$$

(3) *Interest earned*

This model is based on three major considerations: economic quantity, trade credit, and predictive maintenance. Because of the credit period length, there are three cases, (1) when $0\le M\le T_P$ (Figure 2); (2) when $T_P\le M\le T$ (Figure 3); and (3) when $T\le M$ (Figure 4), all depending on credit period length M. The inventory cycle time $T=\dfrac{PT_P}{(d_1+d_2)}$. There are three different types interest earned in the three cases.

Case I: $0 \leq M \leq T_P$

$$TI_{e1} = \left(S_1 \mathrm{i}_e \int_0^M d_1 t dt + S_2 \mathrm{i}_e \int_0^M d_2 t dt\right) \frac{(d_1 + d_2)}{PT_P} = \frac{M^2 (d_1 + d_2) \mathrm{i}_e (d_1 S_1 + d_2 S_2)}{2PT_P}. \tag{2.9}$$

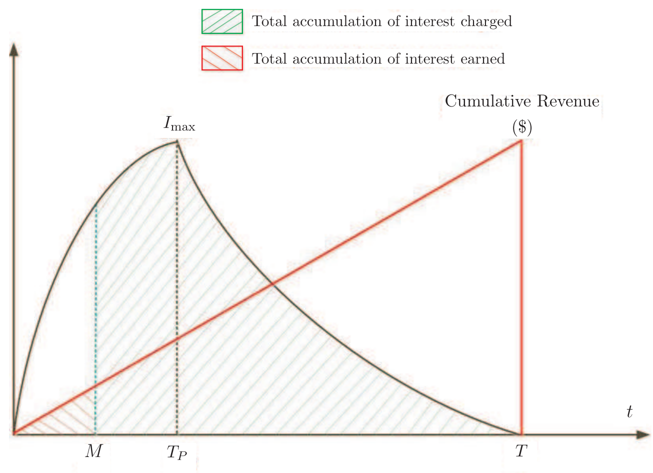

Figure 2: Total accumulation of interest charged and earned when $0 \leq M \leq T_P$.

Case II: $T_P \leq M \leq T$

$$TI_{e2} = \left(S_1 \mathrm{i}_e \int_0^M d_1 t dt + S_2 \mathrm{i}_e \int_0^M d_2 t dt\right) \frac{(d_1 + d_2)}{PT_P} = \frac{M^2 (d_1 + d_2) \mathrm{i}_e (d_1 S_1 + d_2 S_2)}{2PT_P}. \tag{2.10}$$

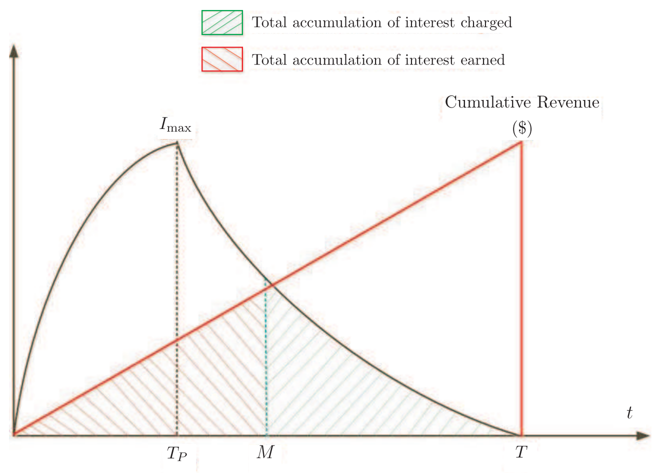

Figure 3: Total accumulation of interest charged and earned when $T_P \leq M \leq T$.

Case III: $T \leq M$

$$\begin{aligned} TI_{e3} =& \Big(S_1 \mathrm{i}_e \int_0^T d_1 t dt + S_2 \mathrm{i}_e \int_0^T d_2 t dt\Big) \frac{(d_1+d_2)}{PT_P} \\ &+ \mathrm{i}_e [S_1 d_1 T(M-T) + S_2 d_2 T(M-T)] \frac{(d_1+d_2)}{PT_P} \\ =& \frac{\mathrm{i}_e T(d_1+d_2)(S_1 d_1 + S_2 d_2)(2M-T)}{2PT_P} \\ =& \frac{(-PT_P + 2M(d_1+d_2))\mathrm{i}_e (d_1 S_1 + d_2 S_2)}{2(d_1+d_2)}. \end{aligned} \tag{2.11}$$

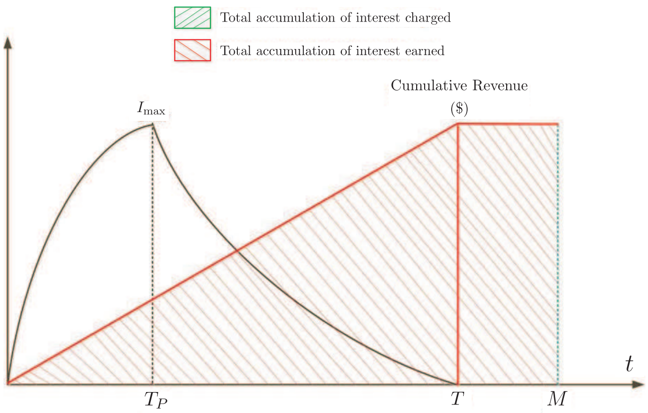

Figure 4: Total accumulation of interest charged and earned when $T \leq M$.

- *The annual cost consists of the following components*:

(1) Annual setup cost

$$TS = \frac{(d_1+d_2)C_S}{PT_P}. \tag{2.12}$$

(2) Annual inventory cost

$$TI = \frac{h \times T_P[P - (d_1+d_2)]}{2}. \tag{2.13}$$

(3) Annual inspection cost

$$TI = \frac{(d_1+d_2)C_{\mathrm{insp}}}{PT_P} \times PT_P = (d_1+d_2)C_{\mathrm{insp}}. \tag{2.14}$$

(4) Annual manufacturing cost

$$TM = \frac{(d_1+d_2)C_m}{PT_P} \times PT_P = (d_1+d_2)C_m. \tag{2.15}$$

(5) Annual predictive maintenance cost

$$TPM = \frac{(d_1 + d_2)}{PT_P} \times \varepsilon \times T_P \times C_{PdM}. \tag{2.16}$$

(6) Annual corrective maintenance cost

$$\begin{aligned} TCM =& \frac{C_{CM}(d_1 + d_2)(1 - e^{-\lambda T_P})}{PT_P} \approx \frac{C_{CM}(d_1 + d_2)\lambda}{P}\Big(1 - \frac{\lambda T_P}{2}\Big) \\ =& \frac{C_M(d_1 + d_2)(\gamma + \eta e^{-\varepsilon})}{P}\Big[1 - \frac{(\gamma + \eta e^{-\varepsilon})T_P}{2}\Big]. \end{aligned} \tag{2.17}$$

(7) There are three different types of interest charged in the three cases (Figures 1∼3).

Case I: $0 \leq M \leq T_P$

$$\begin{aligned} TI_{c1} =& C_m \mathrm{i}_p\Big(\int_M^{T_P} t(P - (d_1 + d_2))dt \int_{T_P}^{T} (d_1 + d_2)(T - t)dt\Big)\frac{(d_1 + d_2)}{PT_P} \\ =& \frac{C_m \mathrm{i}_p(d_1 + d_2)\Big((d_1 + d_2)(M^2 + T^2 - 2T_PT) + P(-M^2 + T_P{}^2)\Big)}{2PT_P} \\ =& \frac{C_m I_P(d_1 + d_2)\Big[(d_1 + d_2)\Big(M^2 + \frac{PT_P{}^2(-2d_1 - 2d_2 + P)}{(d_1+d_2)^2}\Big) + P(-M^2 + T_P{}^2)\Big]}{2PT_P}. \end{aligned} \tag{2.18}$$

Case II: $T_P \leq M \leq T$

$$\begin{aligned} TI_{c2} =& \frac{(d_1 + d_2)}{PT_P} C_m \mathrm{i}_p \int_M^T (d_1 + d_2)(T - t)dt = \frac{C_m \mathrm{i}_p(d_1 + d_2)^2(M - T)^2}{2PT_P} \\ =& \frac{(M(d_1 + d_2) - PT_P)^2 \mathrm{i}_p C_m}{2PT_P}. \end{aligned} \tag{2.19}$$

Case III: $T \leq M$

There is no interest charged in this case.

After summarizing the above costs and revenues, the model can be formulated as three extensions, as below.

Case I: $0 \leq M \leq T_P$

$$\begin{aligned} & ETP_1(T_P, \varepsilon) \\ =& \frac{1}{2}S_1(d_1+d_2)(2-\lambda T_P a_{\mathrm{out}} + a_{\mathrm{in}}(-2+\lambda T_P)) + \frac{1}{2}(d_1+d_2)S_2[a_{\mathrm{out}}\lambda T_P + a_{\mathrm{in}}(2-\lambda T_P)] \\ & + \frac{M^2(d_1+d_2)\mathrm{i}_e(d_1 S_1 + d_2 S_2)}{2T_P} - \frac{(d_1+d_2)C_S}{PT_P} - \frac{C_{CM}\lambda(d_1+d_2)}{P}\Big(1 - \frac{\lambda T_P}{2}\Big) \\ & - \frac{(d_1+d_2)}{PT_P}\varepsilon T_P C_{PdM} - (d_1+d_2)C_m - \frac{hT_P[P-(d_1+d_2)]}{2} - (d_1+d_2)C_{\mathrm{insp}} \\ & - \frac{C_m \mathrm{i}_p(d_1+d_2)\Big[(d_1+d_2)\Big(M^2 + \frac{P(-2d_1-2d_2+P)}{(d_1+d_2)^2}\Big) + P(-M^2+T_P{}^2)\Big]}{2PT_P}. \end{aligned} \tag{2.20}$$

Case II: $T_P \le M \le T$

$$\begin{aligned}
&ETP_2(T_P,\varepsilon)\\
&=\frac{1}{2}S_1(d_1+d_2)(2-\lambda T_P a_{\text{out}}+a_{\text{in}}(-2+\lambda T_P))+\frac{1}{2}(d_1+d_2)S_2[a_{\text{out}}\lambda T_P+a_{\text{in}}(2-\lambda T_P)]\\
&\quad+\frac{M^2(d_1+d_2)\mathrm{i}_e(d_1S_1+d_2S_2)}{2T_P}-\frac{(d_1+d_2)C_S}{PT_P}-(d_1+d_2)C_{\text{insp}}-(d_1+d_2)C_m\\
&\quad-\frac{(d_1+d_2)}{PT_P}\varepsilon T_P C_{PdM}-\frac{hT_P[P-(d_1+d_2)]}{2}-\frac{C_{CM}\lambda(d_1+d_2)}{P}\Big(1-\frac{\lambda T_P}{2}\Big)\\
&\quad-\frac{(M(d_1+d_2)-PT_P)^2\mathrm{i}_pC_m}{2PT_P}. \qquad (2.21)
\end{aligned}$$

Case III: $T \le M$

$$\begin{aligned}
&ETP_3(T_P,\varepsilon)\\
&=\frac{1}{2}S_1(d_1+d_2)(2-\lambda T_P a_{\text{out}}+a_{\text{in}}(-2+\lambda T_P))+\frac{1}{2}(d_1+d_2)S_2[a_{\text{out}}\lambda T_P+a_{\text{in}}(2-\lambda T_P)]\\
&\quad+\frac{(-PT_P+2M(d_1+d_2))\mathrm{i}_e(d_1S_1+d_2S_2)}{2(d_1+d_2)}-\frac{(d_1+d_2)C_S}{PT_P}-(d_1+d_2)C_{\text{insp}}-\frac{d_1+d_2}{PT_P}\varepsilon T_P C_{PdM}\\
&\quad-(d_1+d_2)C_m-\frac{hT_P[P-(d_1+d_2)]}{2}-\frac{C_{CM}\lambda(d_1+d_2)}{P}\Big(1-\frac{\lambda T_P}{2}\Big). \qquad (2.22)
\end{aligned}$$

3. Solution Approach

The objective of the function is to determine the optimal production runtime (T_P^*) and predictive maintenance (ε^*) to maximize the annual profit.

$$ETP(T_P,\varepsilon)=\begin{cases} ETP_1(T_P,\varepsilon),\ 0\le M\le T,\\ ETP_2(T_P,\varepsilon),\ T_P\le M\le T,\\ ETP_3(T_P,\varepsilon),\ M\ge T. \end{cases} \qquad (3.1)$$

To address the problem, three cases are considered.

Case I: $0 \le M \le T_P$

In Case I, the second-order derivative of $ETP_1(T_P,\varepsilon)$ with respect to T_P is

$$\frac{d^2ETP_1(T_P,\varepsilon)}{dT_P{}^2}=\frac{(d_1+d_2)\Big[-2C_S+\mathrm{i}_pC_m(P(2+M^2)-dM^2-\frac{P^2}{d_1+d_2})+\mathrm{i}_eM^2(d_1S_1+d_2S_2)\Big]}{PT_P{}^3}. \qquad (3.2)$$

If $2C_S > \mathrm{i}_pC_m(-dM^2+P(2+M^2)-dM^2-\frac{P^2}{d_1+d_2})+\mathrm{i}_eM^2(d_1S_1+d_2S_2)$, $ETP_1(T_P,\varepsilon)$ is a concave function of T_P. Therefore, the production runtime T_P is derived by solving

$\dfrac{dETP_1(T_P,\varepsilon)}{dT_P}=0$, so we have

$$\begin{aligned}T_{P1}^{*}=&\sqrt{(d_1{+}d_2)}\sqrt{-2C_S{+}\mathrm{i}_pC_m(P(2{+}M^2){-}dM^2{-}\frac{P^2}{d_1{+}d_2}){+}\mathrm{i}_eM^2(d_1S_1{+}d_2S_2)}\\&\Big/\Big[(d_1{+}d_2)(\gamma+\eta e^{-\varepsilon})^2C_{CM}+(2(d_1+d_2)^2-3P(d_1+d_2)+P^2)\mathrm{i}_pC_m\\&+P(h(d_1+d_2-P)+(\gamma+\eta e^{-\varepsilon})(d_1+d_2)(S_1-S_2)(a_{\mathrm{in}}-a_{\mathrm{out}}))\Big]^{1/2}. \qquad (3.3)\end{aligned}$$

To ensure $M\le T_P$ in Case I, we substitute Equation (3.3) into $M\le T_P$ to obtain the below equations.

$$\begin{aligned}2C_S\le&-\frac{M^2[(d_1{+}d_2)(\gamma+\eta e^{-\varepsilon})^2C_{CM}+(2(d_1+d_2)^2-3P(d_1+d_2)+P^2)\mathrm{i}_pC_m]}{(d_1{+}d_2)}\\&+\frac{M^2[P(h(d_1+d_2-P)+(\gamma+\eta e^{-\varepsilon})(d_1+d_2)(S_1-S_2)(a_{\mathrm{in}}-a_{\mathrm{out}}))]}{(d_1{+}d_2)}\\&+\mathrm{i}_pC_m\Big(P(2+M^2)-dM^2-\frac{P^2}{(d_1+d_2)}\Big)+\mathrm{i}_eM^2(d_1S_1+d_2S_2). \qquad (3.4)\end{aligned}$$

If $2C_S\le \mathrm{i}_pC_m(P(2+M^2)-dM^2+-\frac{P^2}{(d_1+d_2)})+\mathrm{i}_eM^2(d_1S_1+d_2S_2)$, which means $\dfrac{d^2ETP_1(T_P,\varepsilon)}{d{T_p}^2}\ge 0$, then $ETP_1(T_P,\varepsilon)$ is not a concave function of T_P. We must use a search algorithm to obtain optimal solutions of the production runtime and predictive maintenance. Let

$$\begin{aligned}G_1=&-\frac{M^2[(d_1{+}d_2)(\gamma+\eta e^{-\varepsilon})^2C_{CM}+(2(d_1+d_2)^2-3P(d_1+d_2)+P^2)\mathrm{i}_pC_m]}{(d_1{+}d_2)}\\&-\frac{M^2[P(h(d_1+d_2-P)+(\gamma+\eta e^{-\varepsilon})(d_1+d_2)(S_1-S_2)(a_{\mathrm{in}}-a_{\mathrm{out}}))]}{(d_1{+}d_2)}\\&+\mathrm{i}_pC_m\Big(P(2+M^2)-dM^2-\frac{P^2}{(d_1+d_2)}\Big)+\mathrm{i}_eM^2(d_1S_1+d_2S_2). \qquad (3.5)\end{aligned}$$

$$G_\alpha=\mathrm{i}_pC_m\Big(P(2+M^2)-dM^2-\frac{P^2}{(d_1+d_2)}\Big)+\mathrm{i}_eM^2(d_1S_1+d_2S_2). \qquad (3.6)$$

Based on the above analyses, we discuss the solution for Case 1 in Lemma 1.

Lemma 1.

(1) *If $G_1<2C_S$, there is no feasible solution in this case.*

(2) *If $G_1\ge 2C_S$ and $2C_S>G_\alpha$, there exists an optimal production runtime T_{P1}^{*}.*

(3) *If $G_1\ge 2C_S$ and $2C_S\le G_\alpha$, use the search algorithm to search the maximum value of $ETR_1(T_P,\varepsilon)$.*

• *Case* II: $T_P \leq M \leq T$

In Case II, the second-order derivative of $ETP_2(T_P, \varepsilon)$ with respect to T_P is

$$\frac{d^2ETR_2(T_P,\varepsilon)}{dT_P{}^2} = \frac{(d_1+d_2)[-2C_S + M^2(\mathrm{i}_e(d_1S_1 + d_2S_2) - (d_1 + d_2)\mathrm{i}_pC_m)]}{PT_P{}^3}. \tag{3.7}$$

If $2C_S > M^2(\mathrm{i}_e(d_1S_1 + d_2S_2) - (d_1 + d_2)\mathrm{i}_pC_m)$, $ETP_2(T_P, \varepsilon)$ is a concave function of T_P. Then, we can derive the production time T_P by solving $\dfrac{dETP_2(T_P,\varepsilon)}{dT_P} = 0$ yields

$$\begin{aligned} T^*_{P2} =& \sqrt{(d_1+d_2)}\sqrt{-2C_S + M^2[\mathrm{i}_e(d_1S_1+d_2S_2) - (d_1 + d_2)\mathrm{i}_pC_m]} \\ & \Big/ \Big[(d_1+d_2)(\gamma + \eta e^{-\varepsilon})^2 C_{CM} + P(h(d_1 + d_2 - P) + P\mathrm{i}_pC_m \\ & + (d_1+d_2)(\gamma+\eta e^{-\varepsilon})(a_{\text{in}} - a_{\text{out}})(S_1 - S_2))\Big]^{1/2}. \end{aligned} \tag{3.8}$$

To ensure $T_P \leq M \leq T$ in Case II, substitute Equation (3.8) into $T_P \leq M \leq T$ ($T = \dfrac{PT_P}{(d_1 + d_2)}$) to obtain the following equations

$$\begin{aligned} & - M^2(d_1+d_2)\Big\{(d_1+d_2)(\gamma+\eta e^{-\varepsilon})^2 C_M + P(h(d_1+d_2-P) + P\mathrm{i}_pC_m \\ & \quad + (d_1+d_2)(\gamma+\eta e^{-\varepsilon})(a_{\text{in}} - a_{\text{out}})(S_1 - S_2))\Big\}\Big/P^2 \\ & \quad + M^2[(d_1+d_2)\mathrm{i}_pC_m + \mathrm{i}_e(d_1S_1 + d_2S_2)] \geq 2C_S \\ \geq & - M\Big\{(d_1+d_2)(\gamma+\eta e^{-\varepsilon})^2 C_{CM} + P(h[-P + (d_1+d_2)] + P\mathrm{i}_pC_m \\ & \quad + (d_1+d_2)(\gamma+\eta e^{-\varepsilon})(a_{\text{in}} - a_{\text{out}})(S_1 - S_2))\Big\}\Big/(d_1+d_2) \\ & \quad + M^2[\mathrm{i}_e(d_1S_1 + d_2S_2) - (d_1+d_2)\mathrm{i}_pC_m]. \end{aligned} \tag{3.9}$$

If $2C_S > M^2(\mathrm{i}_e(d_1S_1 + d_2S_2) - (d_1 + d_2)\mathrm{i}_pC_m)$, $ETR_2(T_P, \varepsilon)$ is not a concave function of T_P. Because of the boundary of T_P ($T_P \in \Big[\dfrac{DM}{P}, M\Big]$), the maximum value of $ETR_2(T_P, \varepsilon)$ will occur at $T_P = \dfrac{DM}{P}$ or $T_P = M$. Assume that:

$$\begin{aligned} G_2 =& -\frac{M^2(d_1+d_2)(\gamma + \eta e^{-\varepsilon})^2 C_{CM}}{(d_1+d_2)} \\ & - \frac{M^2P\{h[-P + (d_1 + d_2)] + P\mathrm{i}_pC_m + (d_1+d_2)(\gamma + \eta e^{-\varepsilon})(a_{\text{in}} - a_{\text{out}})(S_1 - S_2)\}}{(d_1+d_2)} \\ & - M^2[\mathrm{i}_e(d_1S_1 + d_2S_2) - (d_1 + d_2)\mathrm{i}_pC_m] \end{aligned} \tag{3.10}$$

$$\begin{aligned} G_3 =& -\frac{M^2(d_1+d_2)[(d_1+d_2)(\gamma + \eta e^{-\varepsilon})^2 C_{CM}]}{P^2} \\ & - \frac{M^2(d_1+d_2)\{P(h(d_1+d_2-P)+P\mathrm{i}_pC_m+(d_1+d_2)(\gamma+\eta e^{-\varepsilon})(a_{\text{in}}-a_{\text{out}})(S_1-S_2))\}}{P^2} \end{aligned}$$

$$- M^2[\mathrm{i}_e(d_1S_1 + d_2S_2) - (d_1 + d_2)\mathrm{i}_pC_m] \tag{3.11}$$

$$G_\beta = M^2[\mathrm{i}_e(d_1S_1 + d_2S_2) - (d_1 + d_2)\mathrm{i}_pC_m]. \tag{3.12}$$

Based on above analyses, we discuss the solution for Case 2 in Lemma 2.

Lemma 2.

(1) *If* $2C_S < G_2$ *or* $2C_S > G_3$*, there is no feasible solution in these cases.*

(2) *If* $G_2 \le 2C_S \le G_3$ *and* $2C_S > G_\beta$*, there exists an optimal production runtime* T^*_{P2}*.*

(3) *If* $G_2 \le 2C_S \le G_3$ *and* $2C_S \le G_\beta$*, the maximum value of* $ETP_2(T_P, \varepsilon)$ *occurs at* $T_P = \dfrac{DM}{P}$ *or* $T_P = M$*.*

• *Case* III: $T \le M$

In Case III (when $T \le M$), the second derivative of $ETP_3(T_P, \varepsilon)$ with association of T_P is

$$\frac{d^2ETR_3(T_P, \varepsilon)}{dT_P{}^2} = -\frac{2(d_1+d_2)C_S}{PT_P{}^3} < 0 \qquad \forall\, T_P. \tag{3.13}$$

$ETP_3(T_P, \varepsilon)$ is the concave function with respect to T_P. The production runtime T_P that maximizes $ETP_3(T_P, \varepsilon)$ is derived by solving $\dfrac{dETR_3(T_P, \varepsilon)}{dT_P} = 0$:

$$T^*_{P3} = \frac{\sqrt{2}(d_1+d_2)\sqrt{C_S}}{\sqrt{\frac{P^2G_4}{M^2(d_1+d_2)}}} \tag{3.14}$$

where

$$\begin{aligned} G_4 =& \frac{M^2(d_1+d_2)[-(d_1+d_2)^2(\gamma + \eta e^{-\varepsilon})^2C_{CM}]}{P^2} \\ &+ \frac{M^2(d_1+d_2)[-h(d_1+d_2)^2 + hP(d_1+d_2) + P\mathrm{i}_e(S_1d_1 + S_2d_2)]}{P} \\ &+ \frac{M^2(d_1+d_2)(d_1+d_2)^2(\gamma + \eta e^{-\varepsilon})(-a_{\mathrm{in}} + a_{\mathrm{out}})(S_1 - S_2)}{P}. \end{aligned} \tag{3.15}$$

To ensure $T \le M$ in Case III, substitute Equation (3.14) into $T \le M$ ($T = \dfrac{PT_P}{(d_1 + d_2)}$) to obtain the below equations

$$\begin{aligned} 2C_S =& \frac{M^2(d_1+d_2)[-(d_1+d_2)^2(\gamma + \eta e^{-\varepsilon})^2C_{CM}]}{P^2} \\ &+ \frac{M^2(d_1+d_2)[-h(d_1+d_2)^2 + hP(d_1+d_2) + P\mathrm{i}_e(S_1d_1 + S_2d_2)]}{P} \\ &+ \frac{M^2(d_1+d_2)(d_1+d_2)^2(\gamma + \eta e^{-\varepsilon})(-a_{\mathrm{in}} + a_{\mathrm{out}})(S_1 - S_2)}{P}. \end{aligned} \tag{3.16}$$

Based on the above analyses, we discuss the solution for Case 3 in Lemma 3.

Lemma 3.

(1) *If* $2C_S < G_4$*, there exists an optimal production runtime* T^*_{P3}*.*

(2) *If* $2C_S > G_4$*, there is no feasible solution in this case.*

To obtain the optimal value of the predictive maintenance efforts ε^*, we substitute $T^*_{Pi}(\varepsilon)$ into the corresponding $ETP_i(T_P, \varepsilon)$, and it simplifies the functions to be a single decision variable model with ε, i.e.,

$$ETP_i(\varepsilon) = \begin{cases} ETP_1(\varepsilon), & \text{when } 0 \leq M \leq T_P, \\ ETP_2(\varepsilon), & \text{when } T_P \leq M \leq T, \\ ETP_3(\varepsilon), & \text{when } T \leq M. \end{cases} \quad (3.17)$$

The optimal predictive maintenance effort for each case can be obtained by solving $\frac{dETP_i(\varepsilon_i)}{d\varepsilon_i} = 0$, where $i = 1, 2, 3$. It is necessary to verify the second derivative of predictive maintenance ε_i condition of concavity, which means: $\frac{d^2ETP_i(\varepsilon_i)}{d{\varepsilon_i}^2} < 0$, where $i = 1, 2, 3$. Based on Lemmas 1, 2, and 3, the following algorithm can determine optimal values for T^*_P and ε^*.

Algorithm

Step 1: For Case I, if $2C_S > G_\alpha$, go to Step 1.1. If $2C_S \leq G_\alpha$, go to Step 1.3.

Step 1.1: If there exists an ε^*_{11} that satisfies $2C_S \leq G_1(\varepsilon^*_{11})$ and the following conditions, $\frac{d^2ETP_1(\varepsilon^*_{11})}{d\varepsilon^2} < 0$ and $\frac{dETP_1(\varepsilon^*_{11})}{d\varepsilon} = 0$, $\varepsilon^*_1 = \varepsilon^*_{11}$ is the optimal value for Case I. Then, determine $T^{**}_{P1}(\varepsilon^{**}_1) = T^*_{P1}(\varepsilon^*_{11})$ by (3.3), set $ETP^*_1(T^{**}_{P1}, \varepsilon^{**}_1)$ by (2.20), and go to Step 4. Otherwise, go to Step 1.2.

Step 1.2: If there exists the ε^*_{1j}, satisfy $2C_S \leq G_1(\varepsilon^*_{1j})$ and $T^*_{P1}(\varepsilon^*_{1j}) \in [M, T]$. Allow $ETP^*_1(T^{**}_{P1}, \varepsilon^{**}_1) = \text{Max}\{ETP(T^*_{P1}(\varepsilon^*_{1j}))\}$, $(T^{**}_{P1}, \varepsilon^{**}_1)$ is the optimal value for Case I, so go to Step 4; otherwise, $ETP_1(T_{P1}, \varepsilon_1) = \infty$.

Step 1.3: If there exists an ε^*_{12} that satisfies $2C_S \leq G_1(\varepsilon^*_{12})$ and $T_{P12}(\varepsilon^*_{12}) = M$, an ε^*_{13} satisfies $2C_S \leq G_1(\varepsilon^*_{13})$ and $T_{P13}(\varepsilon^*_{13}) = T$. Allow $ETP^*_1(T^{**}_{P1}(T^{**}_{P1}, \varepsilon^{**}_1) = \text{Max}\{ETP_1(T_{P12}(\varepsilon^*_{12})), ETP_1(T_{P13}(\varepsilon^*_{13}))\}$, $(T^{**}_{P1}, \varepsilon^{**}_1)$ is the optimal value for Case I, so go to Step 4; otherwise, $ETP_1(T_{P1}, \varepsilon_1) = \infty$.

Step 2: For Case II, if $2C_S > G_\beta$, go to Step 2.1; if $2C_S \leq G_\beta$, go to Step 2.3.

Step 2.1: If there exists an ε^*_{21} that satisfies $G_2(\varepsilon^*_{21}) \leq 2C_S \leq G_3(\varepsilon^*_{21})$ and the following conditions, $\frac{dETP_2(\varepsilon^*_{21})}{d\varepsilon} = 0$ and $\frac{d^2ETP_2(\varepsilon^*_{21})}{d\varepsilon^2} < 0$, then determine $T^{**}_{P2}(\varepsilon^{**}_2) = T^*_{P2}(\varepsilon^*_{21})$ by (3.8), set $ETP^*_2(T^{**}_{P2}, \varepsilon^{**}_2)$ by (2.21), and go to Step 4. Otherwise, go to Step 2.2.

Step 2.2: If there exists an ε_{22}^* that satisfies $G_2(\varepsilon_{22}^*) \leq 2C_S \leq G_3(\varepsilon_{22}^*)$ and $T_{P22}^*(\varepsilon_{22}^*) = \dfrac{DM}{P}$, an ε_{23}^* satisfies $G_2(\varepsilon_{23}^*) \leq 2C_S \leq G_3(\varepsilon_{23}^*)$, and $T_{P23}^*(\varepsilon_{23}^*) = M$. Allow $ETP_2^*(T_{P2}^{**}, \varepsilon_2^{**}) = \text{Max}\{ETP_2(T_{P22}^*(\varepsilon_{22}^*)), ETP_1(T_{P23}^*(\varepsilon_{23}^*))\}$, then $(T_{P2}^{**}, \varepsilon_2^{**})$ is the optimal value for Case I, so go to Step 4; otherwise, $ETP_2(T_{P2}, \varepsilon_2) = \infty$.

Step 2.3: If there exists an ε_{24}^* that satisfies $G_2(\varepsilon_{24}^*) \leq 2C_S \leq G_3(\varepsilon_{24}^*)$ and $T_{P24}^*(\varepsilon_{24}^*) = \dfrac{DM}{P}$, an ε_{25}^* satisfies $G_2(\varepsilon_{25}^*) \leq 2C_S \leq G_3(\varepsilon_{25}^*)$ and $T_{P25}^*(\varepsilon_{25}^*) = M$. Allow $ETP_2^*(T_{P2}^{**}, \varepsilon_1^{**}) = \text{Max}\{ETP_2(T_{P25}^*(\varepsilon_{25}^*)), ETP_1(T_{P25}^*(\varepsilon_{25}^*))\}$, then $(T_{P2}^{**}, \varepsilon_2^{**})$. is the optimal value for Case I, so go to Step 4; otherwise, $ETP_2(T_{P2}, \varepsilon_2) = \infty$.

Step 3: For Case III.

Step 3.1: If there exists an ε_{31}^* that satisfies $2C_S \leq G_4(\varepsilon_{31}^*)$ and the following conditions, $\dfrac{dETP_3(\varepsilon_{31}^*)}{d\varepsilon} = 0$ and $\dfrac{d^2ETP_3(\varepsilon_{31}^*)}{d\varepsilon^2} < 0$, then determine $T_{P3}^{**}(\varepsilon_3^{**}) = T_{P3}(\varepsilon_{31}^*)$ by (36), set $ETP_3^*(T_{P3}^{**}, \varepsilon_3^{**})$ by (22), and go to Step 4. Otherwise, $ETP_3(T_{P3}, \varepsilon_3) = \infty$.

Step 4: Let $ETR(T_P^*, \varepsilon^*) = \text{Max}\{ETP_1(T_{P1}^{**}, \varepsilon_1^{**}), ETP_2(T_{P2}^{**}, \varepsilon_2^{**}), ETP_3(T_{P3}^{**}, \varepsilon_3^{**})\}$.

4. Numerical Study

4.1. Numerical example

To illustrate the solution procedure used for the model presented in Section 3, we consider a case featuring the following data: $P = 10000$, $d = 8000$ units, $d_1 = 7000$ units, $d_2 = 1000$ units, $I_e = 0.1$, $I_P = 0.15$, $M = 0.1$ year, $h = 20\$$ per unit, $C_{CM} = 300\$$ per time, $C_{\text{insp}} = 5\$$ per unit, $C_m = 15\$$ per unit, $C_{CdM} = 40\$$ per unit time, $C_S = 500\$$ per time, $S_1 = 30\$$ per unit, and $S_2 = 20\$$ per unit. Moreover, we assume that the system is in the in-control state, and the defective rate is 0.05 ($a_{\text{in}} = 0.05$); when the system is in an out-of-control" state, the defective rate is 0.20 ($a_{\text{out}} = 0.20$). The basic system shifting rate before executing predictive maintenance is $\gamma = 1.41$, and the efficiency coefficient of quantifying the predictive maintenance efforts is $\eta = 0.5$.

Using Mathematica 10.0 to run the algorithm, the optimal solution could be found when $M \leq T_P$, i.e., $ETP^*(T_P, \varepsilon) = ETP_1^*(T_P, \varepsilon)$. The optimal values of the objective function and decision variables are listed in Table 1. Figures 5 and 6 illustrate graphically the relationship between the expected total revenue and the two decision variables: the predictive maintenance efforts ε, and the production runtime, T_P.

Table 1: The result of numerical example.

$ETP_1^*(T_P, \varepsilon)$	T_P	ε
70025.7	0.103	2.51

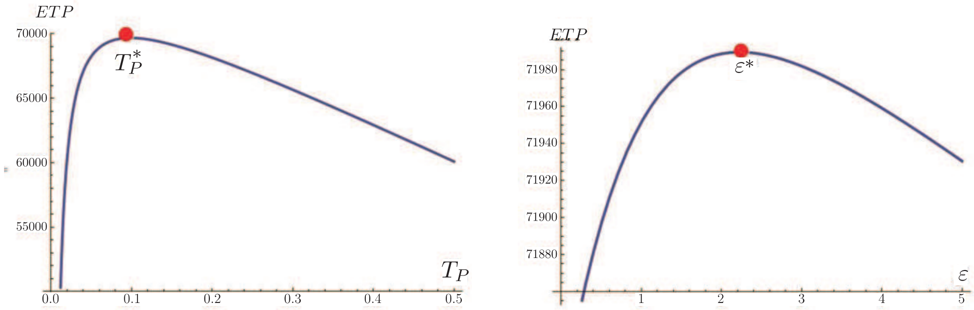

Figure 5: The 2d-figure of expected profit ETP^* with respect to two decision variable.

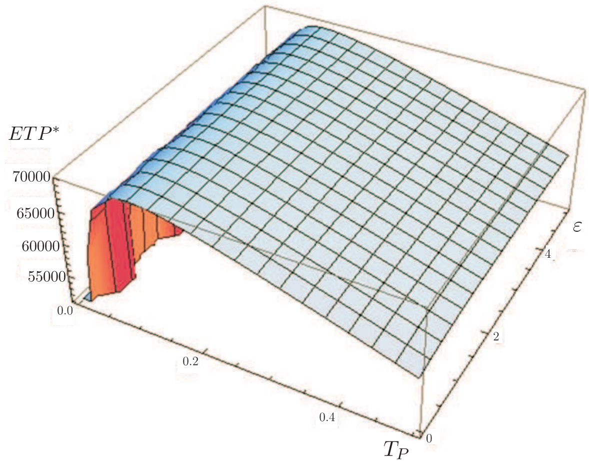

Figure 6: The 3d-figure of expected profit ETP^* with respect to two decision variable.

4.2. Sensitivity analysis

We provide a sensitivity analysis of the optimal ETP to control several parameter values (-50%, -25%, +25%, +50%) in the model. Only one parameter is changed at the same time; other parameters are kept as in the previous section. The results of the sensitivity analysis for the model are listed below.

Table 2: Sensitivity analysis of perfect item selling price.

S_1	ETP	ε	T_P
50%	90456.3	3.165	0.115
25%	87689.5	2.876	0.1106
-25%	-9989.1	2.098	0.1001
-50%	-18973.2	1.813	0.987
Relationship	Positive	Positive	Positive

1. The expected total revenue ETP is significantly influenced by the selling price of perfect item S_1 (Table 2). The total expected profit sharply decreases since the reducing of S_1. Similarly, it also increases with an increase in the selling price of an imperfect item (S_2), credit time (M), and interest earned (I_e). However, the total expected profit decreases with an increase in setup cost (C_S), holding cost (h), corrective maintenance cost (C_{cm}), predictive maintenance cost (C_{PdM}), and interest paid (I_P) (see Figure 7).

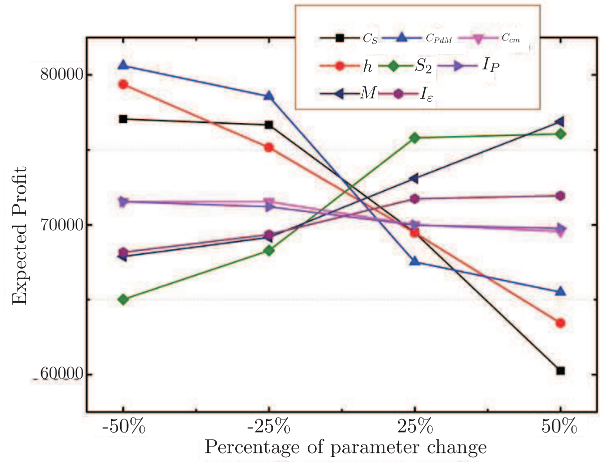

Figure 7: Sensitivity analysis of different parameter on the total profit.

2. The predictive maintenance effort ε increases as the setup cost (C_S), corrective maintenance cost (C_{cm}), and selling price of a perfect item (S_1) increase. However, it decreases with an increase in holding cost (h), predictive maintenance cost (C_{PdM}), selling price of an imperfect item (S_2), credit time (M), interest earned (I_e), and interest paid (I_P) (see Figure 8).

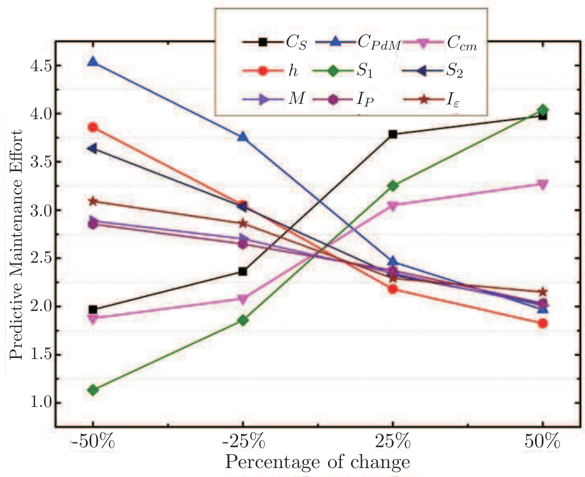

Figure 8: Sensitivity analysis of different parameters on the predictive maintenance effort.

3. The production runtime T_P decreases with an increase in holding cost (h), predictive maintenance cost (C_{PdM}), selling price of an imperfect item (S_2), credit time (M), interest earned (I_e), and interest paid (I_P) (see Figure 9). However, it increases as the setup cost (C_S), corrective maintenance cost (C_{cm}), and the selling price of a perfect item (S_1) increase (see Figure 9).

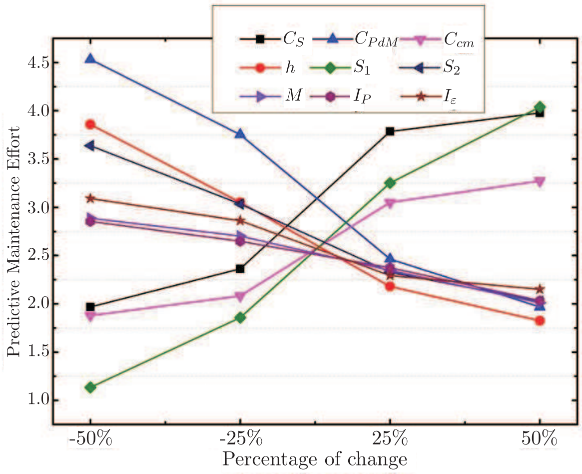

Figure 9: Sensitivity analysis of different parameter on the production runtime.

5. Conclusion

This paper develops an imperfect production model considering predictive maintenance and trade credit. An increase in the predictive maintenance effort reduces the failure rate, the corrective maintenance cost decreases, and the annual profit increases. We determined the optimal production runtime and predictive maintenance effort to maximize the total expected profit. Under trade credit policy, we divided the model into three cases. An algorithm was developed to solve the three-branch of the total expected revenue function. Finally, we provided a numerical example to illustrate the solution procedure and sensitivity analysis to show the influences of system parameters on decisions and profit. The results show that, if the suppliers provide more credit time, the profit of the company could increase by reducing the production time. Especially, the selling price for the perfect item has a significant effect on the profit. A decrease in selling price could make the profit reduce sharply. In a different way, the predictive maintenance effort and production runtime are negatively related to interest earned, credit period, and the interest charged. Therefore, when the credit period and interest earned decrease, the company should examine how to increase the predictive maintenance effort and production runtime to balance the profit.

We only considered trade credit that suppliers provide to retailers. In practice, trade credit is given twice: the suppliers provide trade credit to retailers, and retailers also provide trade credit to end customers. In addition, the demand function is given, and no shortages are considered in this study. Future research may consider other conditions, such as two periods of trade credit, uncertainty demand, allowed shortages, and pricing problems.

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References

[1] Ben-Daya, M. (2002). *The economic production lot-sizing problem with imperfect production processes and imperfect maintenance*, International Journal of Production Economics, Vol.76, No.3, 257-264.

[2] Ben-Daya, M. and Makhdoum, M. (1998). *Integrated production and quality model under various preventive maintenance policies*, Journal of the Operational Research Society, Vol.49, No.8, 840-853.

[3] Chen, S. C., Teng, J. T. and Skouri, K. (2014). *Economic production quantity models for deteriorating items with up-stream full trade credit and down-stream partial trade credit*, International Journal of Production Economics, Vol.155, 302-309.

[4] Chung, K. J. and Huang, Y.-F. (2003). *The optimal cycle time for EPQ inventory model under permissible delay in payments*, International Journal of Production Economics, Vol.84, No.3, 307-318.

[5] Goyal, S. K. (1985). *Economic order quantity under conditions of permissible delay in payments*, Journal of the Operational Research Society, Vol.36, No.4, 335-338. doi:10.1057/jors.1985.56

[6] Huang, Y. F. (2007). *Optimal retailer's replenishment decisions in the EPQ model under two levels of trade credit policy*, European Journal of Operational Research, Vol.176, No.3, 1577-1591.

[7] Huang, Y. F., Weng, M. W., Lee, C. C. and Huang, H. F. (2017, 8-10 Nov. 2017). *An economic production quantity model with imperfect production processes and corrective maintenance under allowable shortages*, Paper presented at the 2017 IEEE 8th International Conference on Awareness Science and Technology (iCAST).

[8] Jamal, A. M. M., Sarker, B. R. and Mondal, S. (2004). *Optimal manufacturing batch size with rework process at a single-stage production system*, Computers & Industrial Engineering, Vol.47, No.1, 77-89.

[9] Kreng, V. B. and Tan, S. J. (2011). *Optimal replenishment decision in an EPQ model with defective items under supply chain trade credit policy*, Expert Systems with Applications, Vol.38, No.8, 9888-9899.

[10] Lee, H. L. and Rosenblatt, M. J. (1987). *Simultaneous Determination of Production Cycle and Inspection Schedules in a Production System*, Management Science, Vol.33, No.9, 1125-1136.

[11] Mobley, R. K (2002). An introduction to Predictive Maintenance, Chapter 1, pp. 5.

[12] Ouyang, L. Y. and Chang, C. T. (2013). *Optimal production lot with imperfect production process under permissible delay in payments and complete backlogging*, Internation Journal of Production Economics, Vol.144, No.2, 610-617.

[13] Pal, B., Sana, S. S. and Chaudhuri, K. (2013). *Maximising profits for an EPQ model with unreliable machine and rework of random defective items*, International Journal of Systems Science, Vol.44, No.3, 582-594.

[14] Sarkar, B., Cárdenas-Barrón, L. E., Sarkar, M. and Singgih, M. L. (2014). *An economic production quantity model with random defective rate, rework process and backorders for a single stage production system*, Journal of Manufacturing Systems, Vol.33, No.3, 423-435.

[15] Sett, B. K., Sarker, S. and Sarker, B. (2017). *Optimal buffer inventory and inspection errors in an imperfect production system with preventive maintenance*, The International Journal of Advanced Manufacturing Technology, Vol.90, 545-560.

[16] Taleizadeh, A. A., Cárdenas-Barrón, L. E. and Mohammadi, B. (2014). *A deterministic multi product single machine EPQ model with backordering, scraped products, rework and interruption in manufacturing process*, International Journal of Production Economics, Vol.150, 9-27.

[17] Tayal, S., Singh, S. R. and Sharma, R. (2016). *An integrated production inventory model for perishable products with trade credit period and investment in preservation technology*, International Journal of Mathematics in Operational Research, Vol.8, No.2, 137-163.

[18] Teng, J. T. and Chang, C. T. (2009). *Optimal manufacturer's replenishment policies in the EPQ model under two levels of trade credit policy*, European Journal of Operational Research, Vol.195, No.2, 358-363.

[19] Terence, J. P. (1997). *Data requirements for the prioritization of predictive building maintenance*, Facilities, Vol.15, No.3/4, 97-104.

[20] Tsao, Y. C., Chen, T. H. and Huang, S. M. (2011). *A production policy considering reworking of imperfect items and trade credit*, Flexible Services and Manufacturing Journal, Vol.23, No.1, 48-63.

[21] Tsao, Y. C., Chen, T. H. and Zhang, Q. H. (2013). *Effects of maintenance policy on an imperfect production system under trade credit*, International Journal of Production Research, Vol.51, No.5, 1549-1562.

[22] Tsao, Y. C., Zhang, Q., Chang, F. C. and Vu, T. L. (2017). *An imperfect production model under Radio Frequency Identification adoption and trade credit*, Applied Mathematical Modelling, Vol.42, 493-508.

[23] Wen, D., Ershun, P., Ying, W. and Wenzhu, L. (2016). *An economic production quantity model for a deteriorating system integrated with predictive maintenance strategy*, Journal of Intelligent Manufacturing, Vol.27, No.6, 1323-1333.

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