



Simultaneous Optimization of Production and Quality in a Deterioration Process

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mean quality characteristic,
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ABSTRACT

Achieving optimal production cycle time for improving manufacturing processes is one of the common problems in production planning. During recent years, different approaches have been developed for solving this problem, but most of them assume that mean quality characteristic is constant over production run length and sets it on customer's target value. However, the process mean may drift from an in-control to an out-of-control at a random point in time. This study aims to select the production cycle time and the initial setting of mean quality characteristic, so that the expected total cost, consisting of quality loss and maintenance costs as well as ordering and holding costs, already considered in the classic models is minimized. To investigate the effect of mean process setting, a computational analysis on a real world example is performed. Results show the superiority of the proposed approach compared to the classical economic production quantity model.

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1. Introduction

In many industries, planning for quantity of production and its scheduling have been consistently associated with restrictions of other manufacturing sectors. Thus, other sectors' policies may affect production planning. For example, maintenance policy, quality control programs, safety and health programs.

Although production planning and quality control are two fundamental and interrelated factors in many industrial processes, they have been often investigated separately in the literature. In other words, the classical models for determining the economic production quantity (EPQ) assume that production process is perfect, which means quality defect never happens. The classical EPQ model has been studied by many researchers. The model basically includes the setup, holding and purchase or manufacturing cost of the product. However, the effect of an imperfect process on the EPQ model has not been studied extensively.

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In some industrial processes, process mean may drift continuously over time in either positive or negative directions. In other words, Production process starts to produce in the in-control state, and after a period of time, the process will eventually drift from in-control state to out-of-control state due to occurrence of an assignable cause such as corrosion, fatigue or cumulative wear. In this situation, production percentage of non-conforming items increases extremely. Hence, in many industries, selection of the optimum process mean setting has been a focal point of research in the area of quality control engineering. This issue arises because the process mean affects the defect rate, material cost, scrap or rework cost and possible losses due to the deviation of product performance from the producer's target value. If the process mean is set too low, then the manufacturing cost might be reduced, but the manufacturer may experience the high rejection cost associated with non-conforming products. On the other hand, if the process mean is set too high, then the proportion of non-conforming products may become low and the manufacturer tends to save rejection costs associated with non-conforming products [1]. However, a higher process mean typically results in a higher cost associated with an increased amount of contents. Therefore, setting the optimal process target mean is an important aspect in the design of any manufacturing process.

Furthermore, a short production run length may result in greater set-up costs and restoration costs, and possibly fewer non-conforming items. A longer production run will result in lower setup costs and restoration costs, and possibly more non-conforming items [2]. Therefore, there is a need to determine an optimal production run length, such that the expected cost per unit time is minimized. Consequently, setting the mean of quality characteristic under consideration and determining the production run length are two important factors of any production system. Effective integration of these two factors will give an industry a competitive advantage.

Production processes generally deteriorate due to consumption or ageing, and the process mean may drift or shift from an in-control to an out-of-control state. As such, without any restoration action, production processes will produce more non-conforming items. on the other hand, if restoration time is longer than normal range, we cannot produce in a normal situation because of long period of run length.

The effect of an imperfect production process was initially studied by Rosenblatt and Lee [3]. The elapsed time to the process shift was assumed to be exponentially distributed, and the optimal production run was found to be shorter than that of the classical EPQ model.

Recently, Kim and Hong [4] have developed an EPQ model to find an optimal production run in a deteriorating process. Brandolese [5] integrated production and maintenance planning to minimize the total production cost. Gibra [6] provided an economic model combining resetting costs and penalty costs for non-conforming products and derived an equation that may be solved graphically to find the optimal resetting time. Arcelus [7] dealt with the problem of obtaining the optimum production run when the quality characteristic of the product is subject to a systematic linear shift in both the mean and variance. Rahim and Lashkari [8], Rahim and Raouf [9], and several others extended Gibra's work and studied the optimal determination of the production run where the process mean is subject to linear drift. In the above studies, it was assumed that the drift of the process mean starts right from the beginning of the production cycle. This assumption, however, is not appropriate for most industrial processes where the deterioration starts at a random point in time resulting from the occurrence of an assignable cause.

Ganeshan [10] introduced the Taguchi quality loss function into inventory modeling development. The purpose was to determine the optimal levels of inventory and production order quantity in order to minimize inventory and quality related costs. Hou [11] considered an economic production quantity model with imperfect production processes, in which the setup cost and process quality are functions of capital expenditure. Rahim [12] and Rahim and Ben-Daya [13] considered the effect of EPQ on the economic design of \bar{x} -control chart. They developed an integrated model for the inventory and quality control problems for a class of deteriorating processes where the in-control period follows a general probability distribution with increasing failure rate. The process was inspected using a sampling frequency that increases with the age of the system. These inspections provided information on the state of the process. In fact, the quality of the product was monitored by a \bar{x} -control chart. Recently, Ben-Daya [14] developed a model integrating the optimization of the design of the control chart, the economic production quantity, and maintenance requirements. Moreover, we can

find many studies on quality characteristics in practical environments in literature such as [15-18].

In the production and quality analysis literature, the economic production quantity has been studied under various conditions. Most of the models discussed are based on the assumptions that the production process never fails, and it always produces items of acceptable quality. In other words, the traditional economic production quantity model assumes that the product is perfect for a manufacturing process. However, a more realistic situation is one in which the quality is not always acceptable because the condition of the production process may deteriorate with time. Hence, the occurrence of a defective product for these models has been neglected.

The role of the production run length and process mean setting in controlling quantity and quality of product is more evident and important than ever. In other words, production quantity and product quality are two interrelated problems. In spite of the mentioned fact, these two problems are often investigated separately. Therefore, developing models that capture interdependency between these two main aspects in the modern production process is an undeniable necessity.

To fill research gaps and overcome the above-mentioned drawbacks, this study integrates the concepts of quality control and inventory control in a unified model. It aims to determine simultaneously the optimal initial setting of the process mean and optimal production cycle length for a process which deteriorates over time in a way that the expected total cost, consisting of the holding, set up, and quality control costs, is minimized. Furthermore, in contrast to the most of existing models which assume the deterioration starts at the beginning of the process, in this paper, it is supposed that the deterioration starts at a random point in time.

The structure of this article is as follows: The problem description is presented in Section 2. In Section 3, the proposed mathematical model is expressed in detail. In Section 4, a numerical example to illustrate important aspects of the proposed integrated model is presented. In Section 5, solution approach to solve the suggested mathematical programming is presented. In Section 6, the sensitivity analysis is given to determine the most effective parameters on the expected total cost per production cycle. Finally, the concluding remarks are given in Section 7.

2. Problem Description

In this paper, we consider a practical manufacturing situation, where a production process starts in good running condition, in which conforming items are produced. After running some time, due to the nature of the process and machine wastage, At a random point in time τ , a assignable cause occurs that leads to the process starting to drift either into a positive or negative direction following the drift function, $W(t, \tau)$. Afterwards, non-conforming items are produced as can be seen in Figure 1.

We consider a process with known and fixed variance that always starts in the in-control state. After a random running time, the process shifts from in-control to out-of-control state. In such a situation, the mean value of the quality characteristic drifts according to a linear function, while the variance is assumed to remain unchanged.

According to deviation from target value, the cost of process mean drift due to drift function is calculated by Taguchi's quadratic loss function. Quality loss in in-control state (Figure 2), due to specification limits and process mean that produces conforming items, is slight. But when process goes in out-of-control state (Figure 3), the quality loss, due to producing not conforming items that are rejected by customer, is more significant.

On the other hand, we should consider product cost with quality cost to determine optimum production run and cycle time. By optimization of quality, replacement, and holding costs, we can obtain optimum initial mean, production run, and production quantity. Therefore, we can achieve an optimum annual expected cost by optimization of initial mean setting and production run length.

The role of the production run length and process mean setting in controlling quantity and quality of product is more evident and important than ever. Production quantity and product quality of the production process are interrelated problems. Traditionally, these two problems are dealt with separately. There is a need for developing models that capture the interdependence between these two main aspects of any modern production process leading to their joint optimization.

However, regardless of production planning, determining the volume of production during the cycle and resetting the process mean cause more cost for producer. In this situation, we need to identify the initial mean setting, μ^* , and the length of the cycle time, T^* , due to optimization of production parameter such as Q^* . The process

mean resetting to its initial setting is usually done at a certain resetting cost. We should pay attention to T^* , because the process mean resetting is done due to process run cycle.

Therefore, the goal is to find an initial mean setting, μ^* , and a cycle length, T^* , which optimize production quantity.

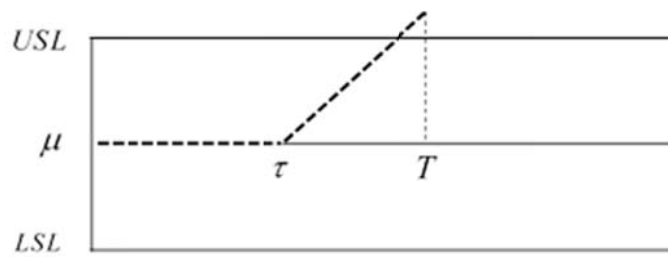


Figure 1. Typical Model

2-1. Notation

We use the following notation for paper to solve presented model.

Tab. 1. Notations

Notation	Description
μ	The initial mean quality characteristic of the product when the process begins in an in-control state having variance σ^2
μ^*	The optimal initial process mean
T	Cycle length
T^*	The optimal cycle length: $T^* = \frac{PT_p^*}{D}$
T_p	Production Run
T_p^*	Optimal Production Run
K	Loss parameter: $(K = A / \Delta^2)$
A	Quality loss index (Reject cost)
Δ	Distance of the mean from the specification limits ($\Delta = USL - \mu_0 \xrightarrow{n=1} \mu_0 + Z_{0.5\alpha} \sigma_0 - \mu_0 \rightarrow \Delta = Z_{0.5\alpha} \sigma_0$)
R	The cost of each installation or replacement
α	Type I of error, When the process is in in-control state
θ	Drift rate per time unit
P	Production rate per time unit
D	Demand rate per time unit
h	Inventory holding cost per unit per time unit
τ	The elapsed time until the occurrence of the assignable cause. It is a random variable and is assumed to be exponentially distributed with a mean of $1/\lambda$;
$f(\tau)$	The density function of the occurrence time of the assignable cause $f(\tau) = \lambda e^{-\lambda\tau}$, $\lambda > 0$, $\tau \geq 0$
ε	A random part that is normally distributed with mean 0 ,variance σ^2

Notation	Description
$y(t, \tau)$	The random variable denoting the quality characteristic of the product at time t $y(t, \tau) = \mu(t, \tau) + \varepsilon$
$\mu(t, \tau)$	The process mean at time t , $\mu(t, \tau) = \begin{cases} \mu & t \leq \tau \\ \mu + W(t, \tau) & t \geq \tau \end{cases}$
$W(t, \tau)$	The drift function
ξ	Target value of the quality characteristic under consideration
ETC	Expected total cost per production cycle

2-2. Assumption

We consider the following assumptions in the proposed model:

1. Loss cost ($L(t, \tau)$) follows a non-linear and quadratic function
2. The shortage cost per unit time is infinite.
4. The variance of quality characteristic is assumed a fixed value and does not shift over time.
5. Every year is assumed to be 250 days.
6. Every day is assumed to be 8 hours.
5. At the end of each production run (T_p), the resetting action is done with installation cost R .

6. The elapsed time until the occurrence of the assignable cause is a random variable and follows an exponential distribution with a mean of $1/\lambda$.

7. Production run (T_p) is the same t_p in the classic EPQ model ($T_p = t_p$).

8. Drift function is dependent on time t and the occurrence time of assignable cause τ , i.e., $w(t, \tau) = \theta(t - \tau)$.

3. The Proposed Mathematical Model

In this section, the expected total cost (ETC), consisting of quality loss, holding, and setup costs, is presented. It is notable that the quality loss cost depends on the considered loss function.

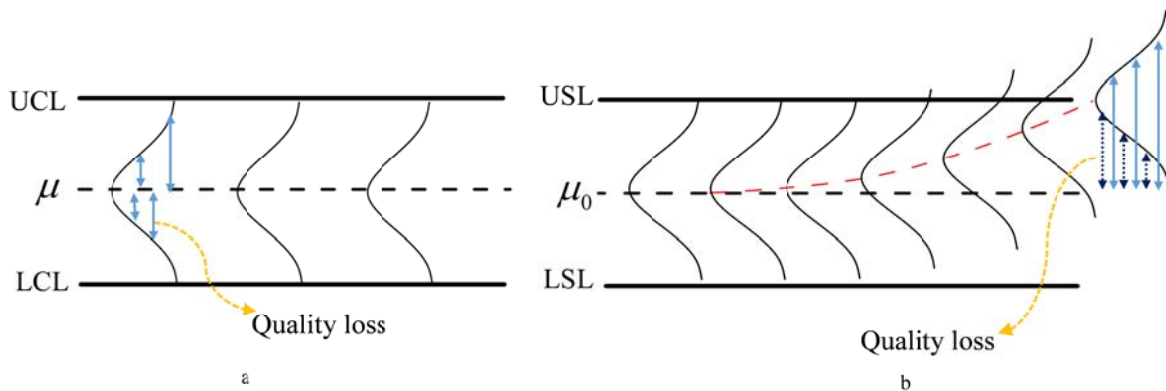


Figure 1. Quality loss, a: in-control state b: Out-of-control state

The expected quality loss depends on the elapsed time until the occurrence of the assignable cause; hence, it can be obtained as follows:

$$E[L(t)] = E(L(t) | t \leq \tau) \times P(t \leq \tau) + E(L(t) | t > \tau) \times P(t > \tau) \tag{1}$$

where τ shows the occurrence time of an assignable cause. In other words, the process produces conforming items before τ , while the process starts drifting after τ . Now, we can calculate quality loss depending on t and τ as in equation (2).

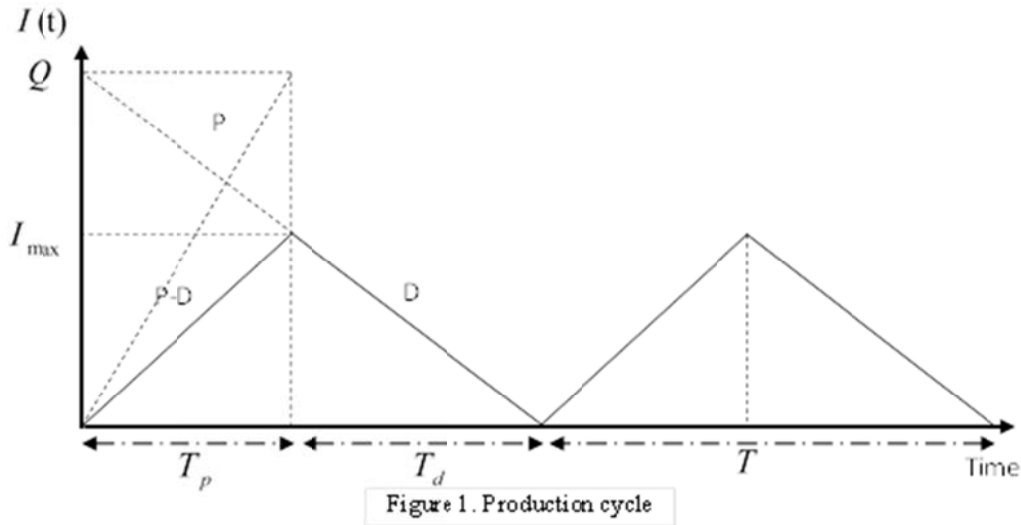
$$L(t, \tau) = K (y(t, \tau) - \xi)^2 \tag{2}$$

Where $y(t, \tau)$ is a random variable that shows value of the quality characteristic of the product at time t .

$$y(t, \tau) = \begin{cases} \mu + \varepsilon & t \leq \tau \\ \mu + w(t, \tau) + \varepsilon & t > \tau \end{cases} \quad (3)$$

According to equations (2) and (3), the quality loss is calculated as follows:

$$L(t, \tau) = \begin{cases} K(\mu + \varepsilon - \xi)^2 & \\ K(\mu + w(t, \tau) + \varepsilon - \xi)^2 & \end{cases} \quad (4)$$



Consequently, the expected quality loss within in-control and out-of-control states for a certain time can be calculated as in equation (5).

$$E[L(t, \tau)] = \begin{cases} KE[(\mu + \varepsilon - \xi)^2] & t \leq \tau \\ KE[(\mu + w(t, \tau) + \varepsilon - \xi)^2] & t > \tau \end{cases} \quad (5)$$

We know that $E[x^2] = Var[x] + (E[x])^2$, where $Var[]$ denotes variance of the quantity in the brackets. Therefore, equation (5) can be rewritten as follows:

$$E[L(t, \tau)] = \begin{cases} KVar[(\mu + \varepsilon - \xi)] + K(E[(\mu + \varepsilon - \xi)])^2 & t \leq \tau \\ KVar[(\mu + w(t, \tau) + \varepsilon - \xi)] + K(E[(\mu + w(t, \tau) + \varepsilon - \xi)])^2 & t > \tau \end{cases} \quad (6)$$

According to equations (6) and (1), the expected quality loss in a certain time can be calculated as follows:

$$E[L(t)] = \left[[KVar[(\mu + \varepsilon - \xi)] + K(E[(\mu + \varepsilon - \xi)])^2] \times e^{-\lambda t} \right. \\ \left. + [KVar[(\mu + w(t, \tau) + \varepsilon - \xi)] + K(E[(\mu + w(t, \tau) + \varepsilon - \xi)])^2] \times (1 - e^{-\lambda t}) \right] \quad (7)$$

If $E[(\mu + \varepsilon - \xi)] = \mu - \xi$, $Var[(\mu + \varepsilon - \xi)] = \sigma^2$ and

$\rho(\mu, t) = KVar[(\mu + w(t, \tau) + \varepsilon - \xi)] + K(E[(\mu + w(t, \tau) + \varepsilon - \xi)])^2 \times (1 - e^{-\lambda t})$ are considered, equation (7) can be simplified as follows:

$$E[L(t)] = K(\sigma^2 + (\mu - \xi)^2) e^{-\lambda t} + \rho(\mu, t) \quad (8)$$

Now, the expected quality loss for a production cycle is calculated by integrating $E[L(t)]$ in the interval $[0, T_p]$

$$L(\mu, T_p) = \int_0^{T_p} E[L(t)] dt = \int_0^{T_p} K(\sigma^2 + (\mu - \xi)^2) e^{-\lambda t} + \rho(\mu, t) dt \tag{9}$$

$$L(\mu, T_p) = \frac{K}{\lambda} (\sigma^2 + (\mu - \xi)^2) (1 - e^{-\lambda T_p}) + \int_0^{T_p} \rho(\mu, t) dt \tag{10}$$

Since drift function is considered as $w(t, \tau) = \theta(t - \tau)$ and τ follows an exponential distribution with parameter λ , the expected quality loss in the time t and the expected quality loss for a production cycle can be rewritten as in equations (11) and (12), respectively.

$$E[L(t)] = K(\sigma^2 + (\mu - \xi)^2) e^{-\lambda t} + K \left(\sigma^2 + \left(\frac{\theta}{\lambda^2}\right) + \left(\mu + \theta t - \left(\frac{\theta}{\lambda}\right) - \xi\right)^2 \right) (1 - e^{-\lambda t}) \tag{11}$$

$$L(\mu, T_p) = \left[\frac{K}{\lambda} (\sigma^2 + (\mu - \xi)^2) (1 - e^{-\lambda T_p}) + \frac{K}{\lambda^3} e^{-\lambda T_p} (\lambda^2 \sigma^2 + \theta) (1 + e^{-\lambda T_p} (1 - \lambda T_p)) + K \int_0^{T_p} \left(\mu + \theta t - \left(\frac{\theta}{\lambda}\right) - \xi \right)^2 [1 - e^{-\lambda t}] dt \right] \tag{12}$$

According to the classical EPQ model, we know that:

$$T = T_p + T_d, \quad T = \frac{Q}{D}, \quad T_p = \frac{Q}{P}, \quad Q = P T_p, \quad T = \frac{P T_p}{D}, \quad T_d = T \left(\frac{P - D}{P} \right)$$

Therefore, according to Figure 3, the setup and holding costs are $\frac{D^2 R}{P^2 T_p}$ and $\frac{h(P - D) T_p}{2}$, respectively.

With respect to equations (1)-(12) and the above explanations, the expected total cost by considering both production and quality in a deterioration process is:

$$ETC = \frac{D^2 R}{P^2 T_p} + \frac{h(P - D) T_p}{2} + \frac{DK}{T_p} \left[\frac{1}{\lambda} [\sigma^2 + (\mu - \xi)^2] (1 - e^{-\lambda T_p}) + \frac{1}{\lambda^3} e^{-\lambda T_p} (\lambda^2 \sigma^2 + \theta) [1 + e^{-\lambda T_p} (1 - \lambda T_p)] + \int_0^{T_p} \left(\mu + \theta t - \left(\frac{\theta}{\lambda}\right) - \xi \right)^2 [1 - e^{-\lambda t}] dt \right] \tag{13}$$

By optimization of ETC , T_p^* will be obtained and by $Q^* = P \times T_p^*$, the optimum production quantity is attained.

4. Solution Approach

Since the decision variables of problem are continuous, and the particle swarm optimization (PSO) has good performance in optimizing such variables, we use PSO algorithm for optimizing the expected total cost. PSO is a robust stochastic optimization technique based on the movement and intelligence of swarms.

PSO is based on the metaphor of social interaction and communication (e.g., fish schooling and bird flocking). This technique uses collaboration among a population of simple search agents, called particles, to find optima in search space. PSO algorithm has effective performance in optimizing difficult problems in a variety of fields. In PSO, the potential solutions

(particles) fly through the problem space by following the current optimum particles. All of the particles are evaluated by the fitness function to be optimized and have velocities that direct the flying of the particles. A general flowchart of solution approach is depicted in Figure 4.

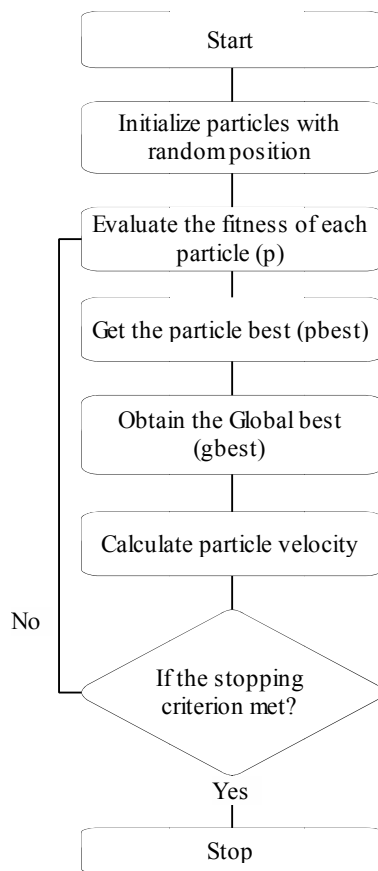


Fig. 4. Solution approach

5. Application of the presented model

The proposed model in this paper can be applied to various engineering problems, such as automotive industry, process industry, etc. A case study is used to illustrate the important aspects of

the proposed integrated model. Our case study is a factory of spring-making in the city of Qom in Iran. Quality characteristic of product is the spring-constant with the scale of Newton per centimeter. Based on the quality control policies, it is assumed that the target value of the quality characteristic is 10, and the acceptable region is in the interval [9, 11]. The process output follows a normal distribution with a known and constant standard deviation $\sigma = 1$. The drift rate is considered to be $\theta = 0.55$ per hour. The process mean drifts at a random point in time that is exponentially distributed at a rate of once every 6.5 hours of operation ($\lambda=0.15$). The replacement cost is estimated to be $R= \$300$. The target mean of the product is assumed to be 10. Confidence level is considered 95% (Type I of error, when the process is in in-control state is 0.05%). The production rate is 350 units per hours. The demand rate is 300 units per hour. It is assumed that the number of working days of year is 200 days and working hours are 8 hours for a day. Therefore, each year is equivalent to 1600 hours. The inventory holding cost per unit per hour is $h=\$0.045$ (\$72per year). The quality loss index is $A=\$0.0025$ per hour (\$4 per year). According to the above assumptions and Table 1: Distance of the mean from the specification limits is $\Delta=0.392$, and consequently the loss parameter is $K=\$0.0163$ per hour (\$26.0800 per year). Results of optimization by PSO algorithm is shown in Table 2.

Tab. 2. Comparison of the proposed model with the EPQ model

Method	μ^*	T_p^*	T^*	Q^*	ETC
Proposed model	10.1174	12.6822	14.7959	4438.8	\$ 62.1475
EPQ	10	15.1186	17.6383	5291.5	\$ 66.4191

Comparison of results of two methods indicate that the EPQ model, because of ignoring the production of non-conforming items, sets the production run length too larger than the proposed model. Furthermore, the presented mathematical model in contrast to the EPQ model, by considering drift function, does not set the initial value of quality characteristic on its target value. Finally, the attained results confirm that the proposed method outperforms the EPQ model with respect to ETC.

6. Sensitivity Analysis

Normalized data in Figures (5)-(8) show the effects of the major parameters consisting of $A, \theta, P,$ and D on optimization result. Sensitivity analysis is done by varying one parameter at each time, while the other parameters remain in their initial values. Effect of the quality loss index A on μ, T_p, ETC is investigated in Figure 5. By increasing the quality loss index, the loss parameter $K = A / \Delta^2$ also increases, and

consequently ETC grows, while μ and T_p decrease.

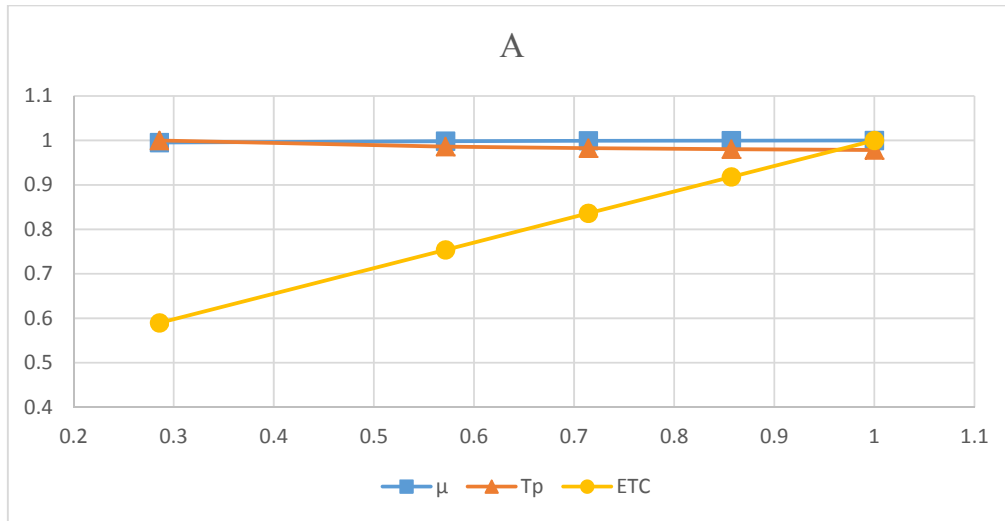


Fig. 5. Effect of quality loss index

Effect of variation on the drift rate is investigated in Figure 6. By increasing in the drift rate, production process will deteriorate in a short time. To reduce the number of the produced non-conforming items in a cycle, the production run

length should be decreased. This issue leads to increasing set up cost and ETC.

As can be seen in Figure 7, increasing the production rate, as expected, results in reduction of production run length and growing of expected total cost and initial value of process mean

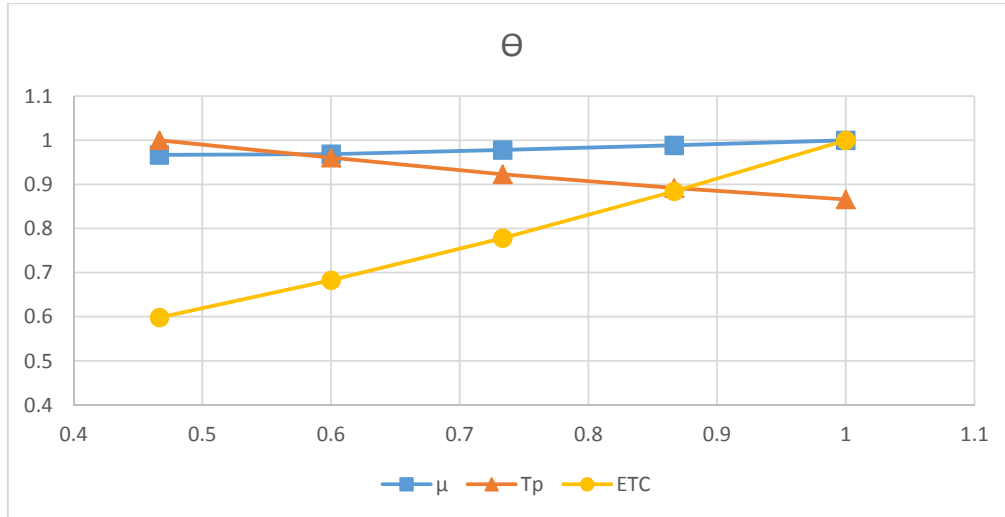


Fig. 6. Effect of θ

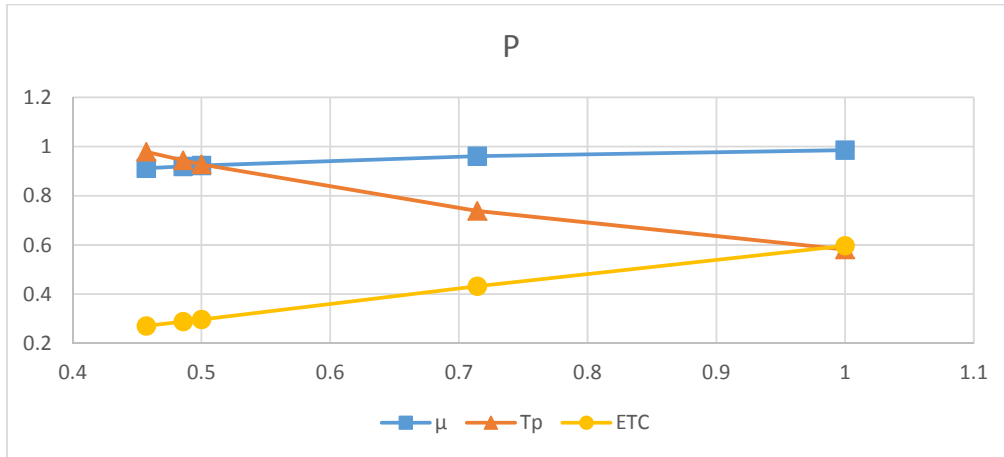


Fig. 7. Effect of Production rate

According to the results illustrated in Figure 8, μ , T_p , and ETC are deeply influenced as the demand rate varies. It can be observed that with an increase in the demand rate, the value

production run length increases dramatically, while the expected total cost and the initial value of process mean decrease.

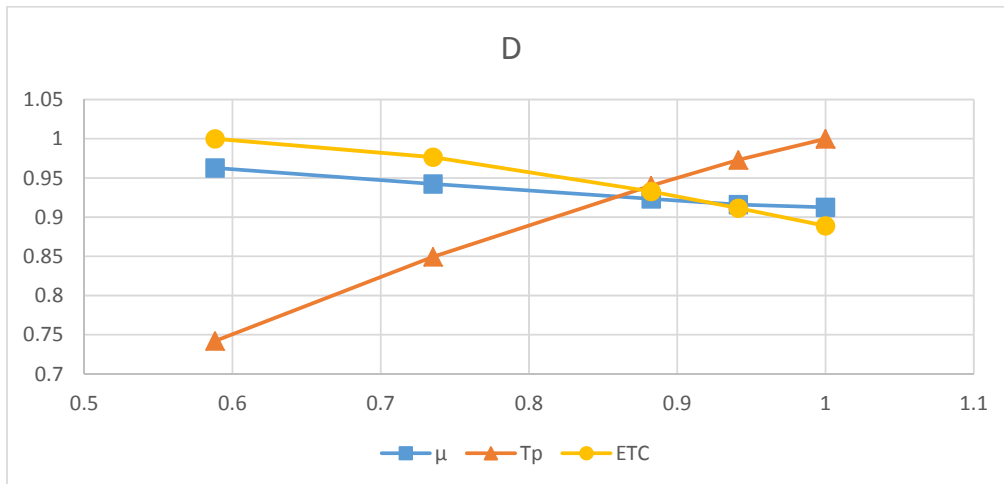


Fig. 8. Effect of Demand rate

7. Conclusion

This paper presented an integrated model for simultaneous optimization of production and quality in a deterioration process with finding the optimal initial setting of the process mean, and the optimal production cycle length. In contrast to the EPQ model, this study considered that the process mean may drift from an in-control state to an out-of-control state at a random point in time. The quality loss due to deviation of quality characteristic from the target value was described by a quadratic function. PSO algorithm was used for optimizing the expected total cost. To investigate the effect of mean process setting, a computational analysis on a real world example was performed. Results showed the superiority of the proposed approach compared to the EPQ

model. A sensitivity analysis has been proposed to find the most effective parameters on decision variables and ETC.

As for future research, we suggest to extend this paper in two directions: first, integration of three concepts of production planning, maintenance policy, and process monitoring; second, simultaneous monitoring of mean and variance of quality characteristic under consideration.

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