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Optimization of preventive maintenance schedule and production lot size

Saad M.A. Suliman *, Sayed Husain Jawad

Mechanical Engineering Department, University of Bahrain, Bahrain

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ABSTRACT

In this research, a developed mathematical model is proposed to optimize the preventive maintenance age and lot size for a single-unit production system producing a single item. The system is assumed to start in an in-control state producing items of acceptable quality and then after a period of production time the system may shift to an out-of-control state producing non-conforming items. The time for the system to shift is a random variable that is assumed to follow a general probability distribution. It is assumed that failure may occur at any time after the system shift to the out-of-control state. The system failure time is also assumed to follow a general probability distribution. The proposed model considers average total values of the maintenance, inventory holding, non-conforming items, and shortage costs. The results found indicated that the introduction of failure possibility decreased the production lot size for a specific preventive maintenance age. Sensitivity analysis is carried out to assess the effect of four cost parameters on model performance. Furthermore, the model is extended to consider the effects of: combining inspection with preventive maintenance; and introducing non-negligible preventive maintenance duration.

1. Introduction and literature review

Maintenance accounts for a huge share of manpower and capital in every industrial firm. Nowadays, with the financial crisis attacking every industry, the importance of maintenance being effective and efficient is one of the top priorities for any firm. This can be achieved through proper maintenance management. One way of "managing maintenance" is through maintenance optimization models.

Dekker (1996) reviewed and analyzed the subject of maintenance optimization models extensively. He tried to answer the questions of whether there has been a value of maintenance optimization models to maintenance management or not, how often these models have been applied successfully and in what sense.

Lee and Rosenblatt (1987) addressed the problem of joint control of production cycles or manufacturing quantities and maintenance by inspection. They solved the problem of simultaneous determination of economic manufacturing quantity (EMQ) and the inspection schedule using an approximation to the cost function. The developed model is the first to address the problem of joint optimization of production lot size and maintenance.

Ben-Daya and Makhdoum (1998) investigated the effect of various preventive maintenance policies on the joint optimization of the economic production quantity (EPQ) or economic manufacturing quantity (EMQ), the economic design of control charts, and the preventive maintenance level. They assumed that the level of the preventive maintenance activities reduces proportionally the shift rate to the out-of-control state. They found that performing preventive maintenance will always yield to reductions in the quality control costs.

Ben-Daya and Hariga (2000) developed a mathematical model representing the effects of imperfect production processes on the economic lot scheduling problem (ELSP). The mathematical model is developed for ELSP taking into account the effect of imperfect quality and process restoration. They have showed that by using the developed model to solve for ELSP, the expected quality cost can be reduced by more than 50%.

Chelbi and Ait-Kadi (2004) developed a mathematical model considering buffer stock size and preventive maintenance schedule of a production system with randomly failing production unit submitted to regular preventive maintenance. The optimum values of the decision variables, namely, buffer size and preventive maintenance schedule, are obtained by trading off the maintenance cost, the inventory holding cost, and the shortage cost such as their sum is minimized.

Chakraborty et al. (2009) developed integrated production, inventory and maintenance models of a deteriorating production system in which the production facility may not only shift from an in-control state to an out-of-control state but also may break down at any random point in a production run. They assumed that in case of machine breakdown, production of the interrupted

* Corresponding author. Fax: +973 17681234.
E-mail address: ssuliman@eng.uob.bh (S.M.A. Suliman).

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lot is aborted and a new production lot is started when the on-hand inventory is depleted after corrective repair.

Chelbi et al. (2008) proposed and modeled an integrated production–maintenance strategy for unreliable production systems producing conforming and non-conforming items. In order to reduce the probability to shift to the out-of-control state, the system is subjected to age-based preventive maintenance strategy. When a shift to the out-of-control state is detected, a restoration action of the system is performed after a preparation period. While being in the out-of-control state, all the non-conforming items produced are rejected. The production cycle ends at the end of the preparation period. The authors assumed that failure may never occur during the preparation period. They focused on finding simultaneously the optimal values of the lot size and the age at which preventive maintenance should be performed.

Maddah et al. (2010) developed two models to determine expected cost and optimal lot size. In one model, it was assumed that imperfect quality items were removed from inventory at no cost. Whereas, the second model assumed that batches of imperfect quality were consolidated and shipped together due to economies of sale in shipping.

Pineyro and Viera (2010) investigated a lot-sizing problem with different demand streams for new and remanufactured items. They provided a mathematical model for the problem which proved to be NP-hard, even under particular cost structures. Aiming at a near optimal solution of the problem, a Tabu-search-based procedure was developed and evaluated.

Rezaei and Davoodi (2011) presented two multi-objective mixed integer non-linear models for multi-period lot-sizing problems involving multiple products and multiple suppliers. Each model was based on three objective functions (cost, quality, and service level) and a set of constraints.

Hongyan and Meissner (2011) looked into the dynamic lot-sizing and resource competition problem of an industry consisting of multiple firms. They developed a capacity model combining the complexity of time-varying demand with cost functions and economies of scale arising from dynamic lot-sizing costs. The competition model was solved, and the existence of capacity equilibrium over the firms and associated optimal dynamic lot-sizing plan for each firm was established.

Within the context of this paper, the objective is to simultaneously determine the optimal values of preventive maintenance schedule and lot size of a single-unit production system which may randomly shift to an out-of-control state under the assumption that failure may occur during the preparation period for its restoration.

2. Model development

2.1. Assumptions

A single unit production system is considered for this work with the following characteristics. The system produces a single item having a constant and continuous demand (D). Every production cycle starts with as-good-as-new system producing items of acceptable quality while it is in control state. The production rate (P) of the system while being in an in-control state is the maximum production rate and is greater than the demand. Whenever the process reaches a maximum inventory level (Z), the production rate is made equal to the demand. The system is submitted to preventive maintenance of negligible duration at times $\lambda * T$, $\lambda = 1, 2, \ldots$, and T is the period between two consecutive preventive maintenance actions. A preventive maintenance action takes a negligible time and restores the system to an as-good-as-new state. After a random production time, the system may shift to an out-of-control state resulting into the production of non-conforming items at a constant rate (α). The time for the system to shift to an out-of-control state is a random variable that will be assumed to follow a known general probability distribution function $F(\cdot)$ with an increasing hazard rate $r(\cdot)$ given by $r(\cdot)=f(\cdot)/F'(\cdot)$, where $f(\cdot)$ and $F'(\cdot)$ are the density function and the complementary distribution function of $F(\cdot)$, respectively. The shift to the out-of-control state is detected instantaneously. When a shift is detected, a preparation period in which the resources needed for the system to be restored is undergone for period (L) after which the restoration action is carried out. The duration of the restoration action is a random variable that will be assumed to follow a known general probability distribution $H(\cdot)$ whose density function is $h(\cdot)$. All the non-conforming items produced during the out-of-control state are rejected immediately. Shortages in the satisfaction of demand are possible. The production ends at the end of the preparation period (L).

The above assumptions are similar to those used by Chelbi et al. (2008). Furthermore, it is assumed that failure may occur at any time after the system shift to the out-of-control state, and unused buffer inventory can be depleted to zero before or after a restoration cycle. The implication of failure will be an increase in the average restoration time (μ), and an increase in the repair cost.

Examples of unreliable single production units in which the production process may shift from "in-control" state to "out-of-control" state at any random time include different types of production systems. Examples in metal cutting are the single- and multi-spindle automatic lathes where one of the tools might signal an "out-of-control" state for some time before failure. Other examples are the hot rolling mills where some defects, like formation of an oxidation layer on the rolls, and edge cracks on the rolled product, are tolerable to a certain limit after which the process should be stopped, i.e. resembling system failure, and a corrective action should be taken. Similar examples can be found in food canning and packaging industry, and in textile and cloth making industry. In such industries the models derived in this paper can enhance the decision making process, specially the decision on maintenance activities that optimize the overall performance of the production system where the demand for the output of the system is satisfied with minimum total cost.

2.2. Model formulation

The developed model will consider the total average costs per unit time as the objective function to be minimized. There are five costs included in this function: setup cost, maintenance cost including preventive and repair costs, inventory holding cost, non-conforming items cost, and shortage cost.

The average restoration cycle length (RCD) is given by

$$RCD = E(X_T) + L + \mu \tag{1}$$

where μ is the average restoration time, and given by

$$\mu = \int_0^{\infty} t dH(t)$$

$E(X_T)$ is given as the average time to shift to an out-of-control state of a system that is submitted to preventive mainteneance at times $T, 2T, 3T \ldots$. The shift occurs during the duration $NT < (X_T) < (N+1)T$. Therefore, the expected time is given as function of the probaility that the shift occurs during the period NT and $(N+1)T$ (Chelbi et al., 2008):

$$E(X_T) = \sum_{N=0}^{\infty} \int_{NT}^{(N+1)T} F'(T)^N F'(t-NT) d\tau = \frac{\int_0^T F'(t)dt}{F(T)} \tag{2}$$