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Integrated preventive maintenance and production decisions for imperfect processes

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ABSTRACT

This paper integrates production, maintenance, and quality for an imperfect process in a multi-period multi-product capacitated lot-sizing context. The production system is modeled as an imperfect machine, whose the status is considered to be either in-control or out-of-control. When the machine is out of control, it produces a fraction of nonconforming items. During each period, this machine is inspected and imperfect preventive maintenance activities are simultaneously performed to reduce its age, proportional to the preventive maintenance level. The objective is to minimize the total cost, while satisfying the demand for all products. Our optimization model allows for a joint selection of the optimal values of production plan, and the maintenance policy, while taking into account quality related costs. A solution algorithm is developed and illustrative numerical examples are presented. It is found that the increase in PM level leads to reductions in quality control costs. Furthermore, if the cost of performing PM is high to the point where it is not compensated for by reductions in the quality related costs, then performing PM is not justifiable. Finally, using non-periodic preventive maintenance with the possibility of different preventive maintenance levels may result in an improvement of the total cost.

1. Introduction

1.1. Motivation and problem description

Maintenance, production, and quality are all strongly linked to each other. On the one hand, as production planning and preventive maintenance (PM) planning are mutually in conflict, these activities are typically performed sequentially. As a result, production and maintenance plans are often not optimal with respect to the objective of minimizing the combined maintenance and production cost. Because of the inter-dependence between production and maintenance, their integration has been shown to be more economical [1,2]. On the other hand, performing PM yields reductions in quality related costs. Therefore, when the extra PM cost is compensated for by the reduction in quality related costs, it is more economical to maintain equipment in top operating conditions through adequate maintenance programs, to ensure high production rate of conforming products [3]. Finally, there is also a clear and strong link between production and quality, since producing nonconforming items may increase the total cost.

In this paper, these three main aspects (i.e., maintenance, production, and quality) are integrated in the same model. We are given a set of products that must be produced in lots on a production system during a specified finite planning horizon including several fixed periods, to satisfy the demand for all products. While the integration of production and PM planning is desirable to reduce the total cost, integrating quality is rather a necessity since the output of the production system is rarely defect-free. The presence of such defective items may lead to additional quality related costs, such as the cost of producing nonconforming items and the restoration cost. Therefore, quality related costs must be taken into account when deciding on the PM strategy and the quantities of items (lot sizes) to be produced. We formulate a constrained optimization model that minimizes the total expected cost, while satisfying the demand for all products over the entire horizon. The objective is to determine an integrated lot-sizing and PM strategy of the system that will minimize the sum of production costs, setup costs, inventory holding costs, backorder costs, preventive maintenance costs, inspection costs, the costs of producing nonconforming items and the restoration cost. We model the production system as a single machine having a general deterioration distribution. During each period, the machine is inspected and imperfect preventive maintenance activities are simultaneously performed to reduce its ages, proportional to the preventive maintenance level [4,5]. The machine is stopped

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Acronyms[1]

EPQ economic production quantity
PM preventive maintenance

Notation

T number of periods
t period index (t=1, 2, …, T)
L length of period t (all periods have the same length)
H planning horizon
G_t average production rate during a period t
g nominal production rate
α fraction of nonconforming items produced when the machine is out-of-control
$f(y)$ probability density function of the time to shift distribution
$F(y)$ cumulative distribution of the time to shift
$\overline{F}(y)$ $(1-F(y))$
$r(y)$ $(f(y)/\overline{F}(y))$, hazard function corresponding to the time to shift distribution
P set of products
p product index ($p \in P$)
d_{pt} demand of product p by the end of period t
h_{pt} inventory holding cost per unit of product p by the end of period t
b_{pt} backorder cost per unit of product p by the end of period t
s_{pt} fixed set-up cost of producing product p in period t
π_{pt} variable cost of producing one unit of product p in period t
k index of PM-inspection interval
CPM_t preventive maintenance cost in period t
Q index of the lowest preventive maintenance level
q index of preventive maintenance level (q=0, 1, …, Q)
CPM_q cost of q preventive maintenance level (CPM_0 is the cost of the maximum preventive maintenance level)
ϑ_k^t length of the kth inspection interval in period t
ψ_k^t time of the kth PM, $\psi_k^t = \sum_{i=1}^{k} \vartheta_i^t$
m_t number of inspections undertaken during each period t
CPM_t vector of dimension (m_t-1) representing the selected preventive maintenance costs during period t
Pr_k^t conditional probability that the machine shifts during period t to the out-of-control state during the time interval (ψ_{k-1}^t, ψ_k^t) given that the machine was in control at time ψ_{k-1}^t
Z_k^t number of nonconforming items produced in (ψ_{k-1}^t, ψ_k^t) in period t
y_k^t actual age right before the kth preventive maintenance in period t
w_k^t actual age right after the kth preventive maintenance in period t
η imperfectness factor of preventive maintenance $(0<\eta\le 1)$
γ_k^t $\left(\gamma_k^t = (\eta)^{k-1}\frac{CPM_q}{CPM_0}\right)$
λ,φ parameters of the time to shift Weibull distribution
τ_k^t detection delay during interval k in period t
ν cost incurred by producing a nonconforming item
β inspection cost
R_k^t restoration cost during interval k in period t
ξ_0, ξ_1 restoration cost parameters
PT_t production time during period t
CR total restoration cost
CN total cost of producing nonconforming items
CQ total cost of preventive maintenance
CPM total cost of preventive maintenance
CI total cost of inspection
TC quantity of product p to be produced in period t
x_{pt} quantity of product p to be produced in period t
I_{pt} inventory level of product p at the end of period t
B_{pt} backorder level of product p at the end of period t
Set_{pt} binary variable, which is equal to 1 if the setup of product p occurs at the end of period t, and 0 otherwise

either when the inspection reveals that it is producing non-conforming products, or at the end of the current period. Once stopped, the machine is restored to the as good as new conditions to be ready for the next production period. The proposed model takes into account the effect of PM level on the cost of nonconforming products and the cost of restoration.

1.2. Prior literature

There is a substantial amount of research dealing with production planning. For example, in [6,7] the authors cover the majority of the advancement in the area. Generally, production planning models tend to be deterministic optimization models designed to minimize inventory, production, and set-up costs in the planning horizon, regarding fulfillment of products demand, and machines capacities. Solution methodologies for corresponding multi-product capacitated lot-sizing problems vary from traditional linear mixed integer programming, and associated branch and bound exact methods to heuristic methods; see for example [8] for a survey.

There exist also a lot of papers dealing with PM planning. For example, the authors of [9,10] have reviewed the literature in this area. Generally, the objective of PM planning models is either to maximize the availability, or to minimize the maintenance cost. These models can be solved by coupling optimization methods with analytical tools or simulation.

There are only a few papers discussing the issue of combining preventive maintenance, quality, and production planning.

In [11], the authors investigate the integration of maintenance and production decisions in a hierarchical production planning environment. In [12], the authors present a production and maintenance planning model for a production system modeled as a single component, subject to cyclical PM with minimal repair at failure. In [2], the authors investigate the value of integrating PM planning and production scheduling for a single machine. While all the above-mentioned papers consider that the production system may experience only two performance levels (perfect functioning or complete failure), Nourelfath et al. [1] have developed an integrated production and PM planning model for a multi-state system [20–26]. For large-size problems, they have proposed a genetic algorithm to deal with the preventive maintenance selection task.

The literature also provides models that deal with the effect of defective items produced by an imperfect process on economic production quantity (EPQ). Rosenblatt and Lee [13] have found that, when the production process is subject to random process deterioration shifting the system from an in-control state to an

[1] The singular and plural of an acronym are always spelled the same.