Int. J. Production Economics 137 (2012) 126–136

Contents lists available at SciVerse ScienceDirect

Int. J. Production Economics

journal homepage: www.elsevier.com/locate/ijpe

Joint optimal production control/preventive maintenance policy for imperfect process manufacturing cell

K. Dhouib [a], A. Gharbi [b,*], M.N. Ben Aziza [a,b]

[a] Mechanical Engineering and Productique Department, École Nationale Supérieure des Ingénieurs de Tunis, MSSDT Laboratory, University of Tunis, 5 Taha Hussein Street, Tunis, Tunisia

[b] Automated Production Engineering Department, École de Technologie Supérieure, Production System Design and Control Laboratory, University of Québec, 1100 Notre-Dame Street West, Montréal, Québec, Canada H3C 1K3

ARTICLE INFO

Article history:
Received 27 November 2009
Accepted 23 January 2012
Available online 1 February 2012

Keywords:
Production-inventory control
Age-based preventive maintenance
Product quality deterioration
Joint optimal policy
Manufacturing cell

ABSTRACT

Production, maintenance, and quality are often modeled as separate problems, despite the strong link that exists between these primary components of any manufacturing system. This paper deals with an integrated approach for the joint optimization of production-inventory control and preventive maintenance policy for a manufacturing cell comprising an imperfect process where the 'in-control' period has a general deterioration distribution. The production-inventory control policy based on the hedging point policy consists of building and maintaining a security stock of finished products in order to respond to demand and to avoid shortages during restoration actions. Restoration actions are planned when the system switches to the 'out-of-control' state and starts producing non-conforming items. The manufacturing cell is also subject to an age-based preventive maintenance policy in order to reduce the shift rate to the 'out-of-control' state. The main objective of this paper is to determine the joint optimal policy that minimizes the overall cost, which is comprised of setup, maintenance, inventory holding, and shortage costs, as well as the cost incurred by producing non-conforming items. A mathematical model is proposed, and the expression of the overall incurred cost is derived and used as a basis for the optimal determination of the joint production-inventory control and preventive maintenance policy. These issues are illustrated using numerical examples. It is found that performing preventive maintenance will yield reductions in the overall incurred cost. Sensitivity analyses are also carried out in order to illustrate the robustness of the proposed methodology.

1. Introduction

Manufacturing system performance is affected mainly by random phenomena such as machine breakdowns and product quality deterioration. In order to respond to demand requests, manufacturing equipment must be maintained in top operating condition through adequate maintenance programs. Despite the fact that production, maintenance, and quality seem to be so closely related to one another, most research does not integrate them into a single model in order to analyze their underlying interactions and their impact on the global performance of manufacturing systems. Indeed, manufacturing systems start in an 'in-control' state, producing conforming items of acceptable quality. However, and after a random span, they shift to the 'out-of-control' state and start producing non-conforming items (Ben-Daya, 2002; Chelbi et al., 2008b; Radhoui et al., 2009). In practice, preventive maintenance should reduce the frequency of transition to the out-of-control state and the production rate of non-conforming items. These aspects will improve the manufacturing system throughput, its capability to respond to the demand by avoiding shortages, and will reduce the overall incurred cost.

Due to complexity considerations, various event-oriented models have been developed to face the uncertainties implicit in the sub-classes of manufacturing systems considered. The different contributions associated with integrated models covered in the literature can be classified as follows: (1) joint production and maintenance problems, (2) joint production and quality problems, and (3) joint production, maintenance, and quality problems.

During the last decades, several production control and maintenance policies have been proposed in order to improve manufacturing system performance. Kimemia and Gershwin (1983), and Akella et al. (1984) have considered the production control problem for systems prone to failures. Akella and Kumar (1986) have introduced the Hedging Point Policy (HPP), which entails that the buffer stock be built up with an excess production capacity and then maintained at its maximum level in order to palliate for interruptions due to breakdowns. Akella and Kumar (1986), and Feng and Xiao (2002) have shown that the HPP policy is optimal

* Corresponding author. Tel.: +1 514 396 8969; fax: +1 514 396 8595.
E-mail addresses: karemdhouib@yahoo.fr (K. Dhouib), ali.gharbi@etsmtl.ca (A. Gharbi), mohamed-naceur.ben-aziza.1@ens.etsmtl.ca (M.N. Ben Aziza).

0925-5273/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.ijpe.2012.01.023

for systems prone to failures described by homogeneous Markov processes (i.e., time-invariant up and down transition rates), and that are thus only subject to corrective maintenance.

To attenuate the impact of failures on the overall performance of manufacturing systems, Barlow and Hunter (1960) introduced the age replacement policy (ARP) concept, which consists of replacing a unit at failure or whenever it reaches a constant threshold age T. They also bring in the notion of the block replacement policy (BRP), under which units are replaced at failure or at fixed intervals kT ($k=1, 2\ldots$) independent of the unit age. Detailed comparisons of the ARP and BRP are proposed by Barlow and Proschan (1965), who find mainly that the ARP is economically superior to the BRP.

A significant portion of the literature is devoted to the cost minimization through combined preventive maintenance and production/inventory control policies. These mathematical models combine BRP or ARP with production/inventory control policies to respond to the demand during maintenance activities (Ki Ling and Hausman, 1997; Salameh and Ghattas, 2001; Tadashi et al., 2001; Chelbi and Ait-Kadi, 2004; Kenné et al., 2007; Gharbi et al., 2007; Chelbi et al., 2008a; Rezg et al., 2008; Berthaut et al., 2011).

In considering manufacturing processes, many authors looked at defective items in order to tackle the economic order/manufacturing quantity problem (i.e., EOQ/EMQ) (Porteus, 1986; Lee and Rosenblatt, 1987; Hariga and Ben-Daya, 1998; Goyal and Cardenas-Barron, 2002; Ben-Daya et al., 2006; Wee et al., 2007; Ben-Daya and Noman, 2008).

More recently, a few researchers have proposed integrated models linking the preventive maintenance, product quality, and production components. Most such proposed models consider manufacturing systems composed of a single imperfect machine manufacturing a single product to respond to a constant and continuous demand. Ben-Daya (1999, 2002), and Ben-Daya and Rahim (2000) propose original models for the joint optimization of the economic manufacturing quantity, the economic design of $\bar{x}$ control charts, and the optimal maintenance level for a single product, deteriorating mono-processor systems. The proposed models do not consider the impact of shortage situations on the optimal policy. Chelbi et al. (2008b) propose an integrated production-maintenance strategy for a single product, single machine system producing conforming and non-conforming items. The proposed model aims to simultaneously find the economic manufacturing quantity and the optimal age T at which preventive maintenance must be performed. Unlike models based on the production control concept (Gharbi et al., 2007; Chelbi et al., 2008a), these models consider that the manufacturing process will produce a specific quantity, the EMQ, and then shut down until the inventory is completely depleted. Radhoui et al. (2009) propose a joint quality control, preventive maintenance, and production control policy for a single product, single machine system producing conforming and non-conforming items. The proposed policy does not consider a continuous inspection of manufactured products, but requires that the quality of each manufactured lot be controlled with a specific size, and according to the percentage of non-conforming items noted, a decision is made to either continue or stop production in order to perform a preventive or a corrective action. A simulation-based approach is considered in order to simultaneously determine the optimal policy parameters, which minimize the expected total cost per time unit.

This paper investigates the contribution of integrating a production-inventory control policy and a preventive maintenance policy in order to attenuate the impact of non-conforming items on the overall performance of a manufacturing cell composed of an automatic machine. The manufacturing cell is dedicated to producing a single product type, and is subject to quality deterioration. The production-inventory control policy is based on the HPP policy (Akella and Kumar, 1986), under which the manufacturing cell operates, initially, at a maximum production rate in order to satisfy demand and to build up a buffer stock. Once the buffer stock is built, the production rate is reduced in order to satisfy the demand rate. This buffer stock is put in place to palliate shortage situations during restoration actions, which for their part are planned when the system switches to the ‘out-of-control’ state and starts producing non-conforming items. An age-based preventive maintenance policy (APM) is also considered in order to reduce the probability of shifting to the ‘out-of-control’ state. After a random period of time spent producing conforming items, the manufacturing cell can shift to the ‘out-of-control’ state and start producing a percentage of non-conforming items. A restoration action of random duration then takes place following a logistic period used to prepare all required resources. The manufacturing cell machine is then restored to the ‘as-good-as-new’ ‘in-control’ state, and once again starts producing conforming items.

A mathematical model considering all possible scenarios that can occur, depending on the instant at which the manufacturing cell shifts to the ‘out-of-control’ state, is proposed, and allows a more realistic consideration of the real behavior of manufacturing cells. The model determines the joint optimal production-inventory control and age-based preventive maintenance policy (i.e., the HPP/APM policy), which minimizes the total average cost per time unit over an infinite horizon. The total cost includes the setup, preventive maintenance, restoration, inventory holding, and the shortage costs, as well as the costs incurred by producing non-conforming items. A solution procedure is also proposed to assess the optimal inventory size and the age at which preventive maintenance actions must be performed.

The remainder of the paper is organized as follows. The system description and its dynamic and stochastic behaviors are discussed in Section 2. Section 2 also presents basic notations and assumptions. The joint production-inventory control, preventive maintenance, and product quality model is developed in Section 3. Section 4 presents a numerical procedure for solving the proposed model, some numerical results to illustrate important issues related to the model, and a sensitivity analysis to demonstrate its robustness. Finally, Section 5 contains a summary of the paper and some concluding remarks.

2. Manufacturing system description

2.1. System description

Consider a manufacturing cell composed of an automatic machine dedicated to producing a single product type to satisfy a constant and continuous demand at rate d. The automatic machine can operate at maximum capacity at rate U_{max}, where $U_{max} > d$. The manufacturing cell is subject to random perturbations caused by product quality deterioration. Initially, the manufacturing cell starts in an ‘in-control’ state, producing conforming items of acceptable quality. After a random operating period (τ), the manufacturing process may shift from the ‘in-control’ state to the ‘out-of-control’ state and starts producing a percentage (α) of non-conforming items. In spite of out-of-order situations where the production process is aborted, during out-of-control situations, the manufacturing cell continues to produce conforming and non-conforming items. The automatic manufacturing cell machine allows the instantaneous detection of the ‘out-of-control’ state. The ‘in-control’ state period is a random variable with general probability distribution having an increasing hazard rate. $f(\tau)$ and $F(\tau)$ are, respectively, the density and distribution functions associated with the random variable τ.