Omega 39 (2011) 642–654

Contents lists available at ScienceDirect

Omega

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

Joint modified block replacement and production/inventory control policy for a failure-prone manufacturing cell

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ARTICLE INFO

Article history:
Received 17 September 2009
Accepted 21 January 2011
Processed by B. Lev
Available online 16 February 2011

Keywords:
Production/inventory control
Block/age replacement policies
Modified block replacement policy
Simulation modeling
Response surface methodology

ABSTRACT

This paper considers a joint preventive maintenance (PM) and production/inventory control policy of an unreliable single machine, mono-product manufacturing cell with stochastic non-negligible corrective and preventive delays. The production/inventory control policy, which is based on the hedging point policy (HPP), consists in building and maintaining a safety stock of finished products in order to respond to demand and to avoid shortages during maintenance actions. Without considering the impact of preventive and corrective actions on the overall performance of the production system, most authors working in the reliability and maintainability domains confirm that the age-based preventive maintenance policy (ARP) outperforms the classical block-replacement policy (BRP). In order to reduce wastage incurred by the classical BRP, we consider a modified block replacement policy (MBRP), which consists in canceling a preventive maintenance action if the time elapsed since the last maintenance action exceeds a specified time threshold. The main objective of this paper is to determine the joint optimal policy that minimizes the overall cost, which is composed of corrective and preventive maintenance costs as well as inventory holding and backlog costs. A simulation model mimicking the dynamic and stochastic behavior of the manufacturing cell, based on more realistic considerations of the real behavior of industrial manufacturing cells, is proposed. Based on simulation results, the joint optimal MBRP/HPP parameters are obtained through a numerical approach that combines design of experiment, analysis of variance and response surface methodologies. The joint optimal MBRP/HPP policy is compared to classical joint ARP/HPP and BRP/HPP optimal policies, and the results show that the proposed MBRP/HPP outperforms the latter. Sensitivity analyses are also carried out in order to confirm the superiority of the proposed MBRP/HPP, and it is observed that for practitioners, the proposed joint MBRP/HPP offers not only cost savings, but is also easy to manage, as compared to the ARP/HPP policy.

1. Introduction

The bulk of industrial capital is composed of systems that produce goods and delivery services. As these systems are prone to failure with usage and age, interest in the development of efficient maintenance strategies has grown exponentially [1,2]. Maintenance activities restore a system to a specified condition, and can be categorized under corrective and preventive actions. Corrective maintenance (CM) occurs at failure, while preventive maintenance (PM) occurs while a system is operating, which implies systematic inspection, detection and prevention of failures [3]. The objective is to carry out a trade-off between maximizing the system's utilization and avoiding failures as much as possible in order to reduce maintenance costs and improve system reliability and availability [4].

Barlow and Hunter [5] introduced the concept of the age replacement PM policy (ARP), which consists of replacing a unit at failure or whenever it reaches a constant age T, and that of the block replacement PM policy (BRP), under which units are replaced at failure or at fixed intervals kT ($k=1, 2\ldots$), irrespective of the unit age. Detailed comparisons of the ARP and BRP are proposed by Barlow and Proschan [6], and mainly provide that the ARP is economically superior to the BRP. Although the BRP is more wasteful (i.e., almost new components are replaced when failures occur shortly before planned PM), it seems more practical to implement and to manage than the ARP since it does not require tracking unit ages and does not modify the PM planning

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doi:10.1016/j.omega.2011.01.006

after each maintenance operation. Several approaches have been proposed in order to improve the performance of the classical BRP: (1) Barlow and Hunter [5] proposed the concept of minimal repair at failure (i.e., a minimally repaired system is restored to its "condition just prior to failure"); (2) Cox [7] and Blaming [8] proposed the concept of inactivity (i.e., if the unit fails not long before the planned PM, it is maintained in a down state until the next PM); (3) Bhat [9], Tango [10], and Murthy and Nguyen [11] proposed using used items (i.e., if the equipment fails not long before the PM, then the unit is replaced with a used item); and (4) Tango proposed using less reliable items [12] (i.e., if the equipment fails not long before the PM instant, the unit is replaced with a new, less reliable item).

Berg and Epstein [13], as well as Archibald and Dekker [14], proposed a modified block replacement policy (MBRP), under which PM actions are performed at fixed intervals if the time elapsed since the last maintenance action exceeds a fixed threshold. Otherwise, the PM action is canceled, and the last installed unit is not removed, and is kept in operation. The authors showed that the MBRP strategy is better than the BRP policy, and almost as good as the ARP policy in terms of maintenance cost, when maintenance durations are negligible, while being rather simple to implement and to control in practice. For constant maintenance durations, the MBRP policy enhances the maintenance cost and the average availability of the machine as compared to the BRP policy [15].

In order to tackle these optimization problems, including complex renewal functions, most researchers consider that PM and CM durations are negligible with respect to the item's lifetime. However, in most practical situations, especially for manufacturing cells, which typically operate at high utilization rates (70–80%), production interruptions due to maintenance not only affect the average system availability [16], but also its capacity to fulfill demand, and may result in shortage situations. In order to reduce the impact of random phenomena and shortage situations due to demand variability, process quality deterioration and machine breakdowns on the overall performance of manufacturing systems, buffer inventory has been often considered [3,17,18]. Scheduling in this environment has also attracted many researchers, as maintenance helps improve production efficiency or product quality but it extends the makespan and may cause job tardiness [19,20].

Joint consideration of production planning and corrective maintenance problems in manufacturing systems has been tackled using the optimal control theory. To control the flow rates of parts through a system subject to random failures and repairs, Kimemia and Gerschwin [21] and Akella and Kumar [22] introduced the hedging point policy (HPP) concept. The HPP entails the build-up and preservation of a final product safety stock while the machine is operational in order to hedge against future shortages caused by machine failures. The optimality of the HPP has been demonstrated for failure and repair times described by homogeneous Markov processes, and therefore, for a failure replacement maintenance strategy, in the case of constant demand rate [22] and stochastic demand rate [23]. For general failure and repair time distributions, the optimal control policy cannot be solved analytically [24,25], but the structure of the optimal inventory policy can be approximated by the HPP [26–28].

A significant branch of the literature is dedicated to minimizing the cost of combined preventive maintenance and production/inventory control policies, by considering the dynamics of a manufacturing system (buffer inventory level and machine state) and renewal approach during a maintenance cycle with constant or stochastic maintenance durations. Most of the proposed models considered failure-prone manufacturing systems composed of a single machine, and manufacturing a single product in order to respond to a constant and continuous demand. These mathematical models combined BRP or ARP with a production/inventory control policy that consists in building up and maintaining a buffer stock to respond to demand during maintenance operations [29–32]. For tractability considerations, they introduced simplifying restrictive assumptions such as the one that there are no breakdowns on the machine during the build-up and depletion phases of the buffer stock. Moreover, they assumed that in shortage situations, unfulfilled demand is simply considered as lost sales, and is not backlogged at all. These assumptions are used to simplify the complex mathematical models by making the inventory level periodic with the maintenance cycle. However, the probability of a machine failing during its early life cannot be neglected, because failures during build-up periods may result in shortage situations and in high penalty costs. Based on simulation results, Rezg et al. [33] showed that this assumption leads to different control parameters and to a 5% difference between incurred costs. In more recent works, Gharbi et al. [34] and Rezg et al. [35] relaxed this assumption. However, they considered that in surplus situations, the maintained machine remains non-operational until the complete depletion of the safety stock. In practical situations, breakdowns may occur during the build-up of buffer stock, and the inventory level at the end of a maintenance cycle is not necessarily periodic with stochastic maintenance durations. Chelbi and Ait-Kadi [36] also noted that the expression of the maintenance and inventory cost involves the sum of random variables (i.e., time between failures plus CM duration), which are hard to compute for most probability distributions. Furthermore, all the papers dealing with joint preventive maintenance and production/inventory control policies only considered classical ARP or BRP. Although the MBRP represents an attractive trade-off between the BRP and the ARP, it has, to our knowledge, never been considered for non-negligible and stochastic maintenance durations, or with inventory control policies.

In this paper, we propose a joint preventive maintenance and production/inventory control policy based on MBRP and hedging point policies (HPP) for a mono-product, single-machine manufacturing cell. This paper relaxes the aforementioned assumptions and considers that: (1) breakdowns are allowed during build-up phases of the finished goods inventory; (2) the inventory level is not necessarily periodic with the maintenance cycle; (3) maintenance actions have non-negligible delays; and (4) unmet demand due to shortage situations is backlogged, instead of being lost. A simulation model is proposed to mimic the real dynamic and stochastic behavior of the manufacturing cell under the joint MBRP/HPP policy. The main objective of this paper is to compare the long-run average maintenance and inventory total cost of MBRP, ARP and BRP when combined with HPP, in order to determine the best joint preventive maintenance and production/inventory control policy. The joint optimal MBRP/HPP, ARP/HPP and BRP/HPP policies are each obtained through design of experiments, simulation analysis, and response surface methodology. This flexible resolution approach allows the exploration of the effects of a wide range of cost and time parameters on the control policies.

The rest of the paper is organized as follows: Section 2 presents the system description, the assumptions, and the structure of the three proposed control policies. The resolution approach based on simulation modeling, design of experiments, analysis of variance, and response surface methodology is presented in Section 3. Section 4 validates the proposed resolution approach and then exposes the optimal solution for a specific basic case. Section 5 provides a sensitivity analysis of the total cost with respect to corrective, preventive, inventory holding, and shortage costs. Section 6 specifically investigates the impact