Journal of Manufacturing Systems 35 (2015) 191–205

Contents lists available at ScienceDirect

Journal of Manufacturing Systems

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

Technical Paper

Joint optimization of preventive maintenance and inventory policies for multi-unit systems subject to deteriorating spare part inventory

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ARTICLE INFO

Article history:
Received 20 July 2013
Received in revised form 7 January 2015
Accepted 18 January 2015
Available online 7 February 2015

Keywords:
Joint optimization
Deteriorating inventory
Block replacement
Periodic review inventory
Multi-unit systems

ABSTRACT

The interconnection of maintenance and spare part inventory management often puzzles managers and researchers. The deterioration of the inventory affects decision-making and increases losses. Block replacement and periodic review inventory policies were here used to evaluate a joint optimization problem for multi-unit systems in the presence of inventory deterioration. The deterministic deteriorating inventory (DDI) model was used to describe deteriorating inventory when deteriorating inventory data were available and the stochastic deteriorating inventory (SDI) model was used when they were not. Analytical joint optimization models were established, and the preventive replacement interval and the maximum inventory level served as decision variables to minimize the expected system total cost rate. This work proved the existence of the optimal maximum inventory level and gave the uniqueness condition under the DDI model. Numerical experiments based on the electric locomotives in Slovenian Railways were performed to confirm the effectiveness of the proposed models. Results showed the total cost rate to be sensitive to the maximum inventory level, which indicates that the research of this work is necessary. Further, the optimal preventive replacement interval was reduced and the optimal maximum inventory level was increased to balance the influence of deteriorating inventory. Monte Carlo experiments were used to show that the proposed policy is better than policies that do not take deteriorating inventory into account.

1. Introduction

Equipment may fail during actual production processes, and maintenance is often needed to restore the equipment to a good condition [1–3]. To perform successful maintenance, a company/plant needs an inventory of spare parts, such as drills, pumps and motors in a manufacturing shop. Maintenance relies highly on the availability of spare parts to reduce the equipment downtime and to allow the system to perform its anticipated functions [4]. However, when making maintenance decisions during the operation of a company/plant, managers have to face the following problems:

(1) Are the spare parts in a good condition? Due to the lack of an ideal inventory environment in practice, spares such as electronic components, mechanical elements, lubricating oil, gasoline, and filters are inevitably subject to degradation in the industrial environment. When spare parts significantly degrade or even fail, they cannot support maintenance procedures and this can result in further inventory deterioration. If spares are not in good condition, the risk of "shortage of spares" will be increased.

(2) Is it best to have a large supply of spare parts? To ensure the availability of spare parts, many places tend to overstock them. It prevents the "shortage of spares", but the "excess of spares" brings its own problems. Managers have extra expenditures purchasing spares, renting storage spaces, and maintaining the parts. Increasing the number of available spares also increases the number of failures. For example, many ocean vessels bring abundant spares during their voyage, but many of them fail because of the harsh ocean environment, rather than from maintenance procedures. More spare parts may not necessarily be better.

(3) What is the relationship between maintenance and spare parts inventory? Maintenance and inventory influence mutually. Maintenance is the main source of spare parts consumption and spare parts are the precondition for performing maintenance. Too frequent maintenance

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http://dx.doi.org/10.1016/j.jmsy.2015.01.002
0278-6125/

may result in more spares consumption, but less maintenance may increase the risk of system downtime. “shortage of spares” postpones the maintenance procedures, and may increase equipment downtime, but “excess of spares” involves extra expenditures. In addition, as illustrated in (1) and (2), the influence of deteriorating spare part inventory should not be ignored, which directly impacts the level of spare parts and the availability of maintenance. Decision makers must simultaneously determine the frequency of maintenance, the ordering time and the quantity of spare parts, especially in the case of deteriorating spare part inventory.

There are previous studies that have considered maintenance and inventory simultaneously. In 1968, Falkner mentioned the joint optimization of maintenance and inventory policies for a single-unit multi-spare system in a finite planning horizon [5]. Kaio and Osaki introduced a joint optimization policy that only considered inventory cost [6]. Their conclusions are not optimal because they ignored the important tradeoff between maintenance-related costs and inventory-related costs. When the two costs are considered together, production may improve. In one example addressing a motor block manufacturing line, joint optimization brought a 53% reduction in total annual maintenance cost and 6% improvement in average monthly production [7]. Van Horenbeek et al. reviewed relevant work and classified them based on the combination of maintenance policy (block-based, age-based, and condition-based) and inventory policy (periodic review and continuous review) [8].

Joint optimization models can be divided into simulation models and mathematical programming models. The former have been used in joint models about block replacement and continuous review inventory policies [7], age-based maintenance and continuous review inventory policies [9], and condition-based maintenance related joint policies for multi-unit systems [10]. It is a good choice when mathematical models cannot be established. However, it has two main drawbacks: (1) optimal analysis is difficult, and the result may not be optimal; (2) due to randomness, each round of simulation generates a different process, and the results may not be fully repeatable. Mathematical programming models are usually based on renewal theory, and they have been used in the joint optimization problem where renewal cycle can be easily determined. For example, the joint models have been used in age-based maintenance and periodic review inventory policies for single-unit systems [11], condition-based maintenance related joint policies for single-unit systems [12], and block replacement and periodic review inventory policies [13–17]. The last joint policies have been widely studied, because they are commonly used in practice and have good time synchronization properties for multi-unit systems.

The existing joint optimization studies only considered problem (2) and (3), but partially ignored the influence of inventory deterioration. The sensitivity analysis conclusions in Brezavšček and Hudoklin showed that 10% decrease of the maximum inventory level led to a 97.4% increase in the total cost rate [14]. This indicated that the influence of inventory deterioration on modeling and decision making should not be totally ignored, and the little changes in inventory may cause the total cost to grow quickly. In fact, some studies have already considered the deteriorating inventory modeling. Ghare and Schrader observed that certain commodities shrink over time in approximate proportion to a negative exponential function of time [18]. They developed an exponentially decaying inventory model, which later became a classical model in inventory managements (please refer to Section 4.1). Based on the model, many studies have been performed on deteriorating inventory models [19–21]. However, these studies only focus on problem (1), and maintenance decisions are not considered.

In this paper, the joint optimization model of block replacement and periodic review inventory policies was considered for a multi-unit system under the influence of deteriorating inventory. It is here proposed that the deterministic deteriorating inventory (DDI) model be used when the deteriorating inventory data are fully available. These data may be unavailable in practice, so it is also proposed the stochastic deteriorating inventory (SDI) model. Analytical optimization models were established based on these models, and the preventive replacement interval and the maximum inventory level were chosen as decision variables to minimize the expected system total cost rate. The existence and uniqueness of the optimal maximum inventory level were also discussed in detail.

The rest of the paper is organized as follows: Section 2 presents the system and policy descriptions. Optimization modeling is presented in Section 3. Sections 4 and 5 discuss the joint policy under the DDI and SDI models, respectively. Section 6 provides the numerical experiments. Section 7 concludes the paper and summarizes the main results.

2. Model descriptions

2.1. Acronyms and notations

CDF	cumulative distribution function
PDF	probability density function
DDI	deterministic deteriorating inventory
SDI	stochastic deteriorating inventory
CR	corrective replacement
PR	preventive replacement
n	number of identical components in the system
T	PR interval, also the renewal cycle length
S	maximam inventory level
S_a	expected initial inventory level just after PR
X	number of CR during cycle T for only one component
X_n	number of CR during cycle T for n components
Y	expected initial inventory level just after PR
τ	procurement lead time
μ	expected component failure time
c_{pr}, c_{cr}	cost of component PR, CR
c_h, c_s	holding cost, shortage loss per spare per unit per time
K	set-up cost for placing an order
c_{sp}	cost for purchasing a spare
C_M	expected maintenance cost in a PR cycle