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Innovative Applications of O.R.

Joint optimization of spare parts ordering and maintenance policies for multiple identical items subject to silent failures

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ABSTRACT

In this paper the joint maintenance and spare parts ordering problem for more than one identical operating items is studied. The operating items may suffer two types of silent failures: a minor failure, which results in item malfunctioning, and a major failure, which renders the item completely out-of-function. Inspections are periodically held to detect any failures and the inspected items are preventively maintained, repaired or replaced according to their condition. Two ordering policies are investigated to supply the necessary spare parts: a periodic review and a continuous review policy. The expected total maintenance and inventory cost per time unit is derived and the proposed models are optimized for real case data. In addition, the sensitivity of the proposed models is studied through numerical examples and the effect of some key problem characteristics on the optimal decisions is discussed.

1. Introduction

Maintenance policies for stochastically failing systems have received great attention from researchers during the last decades. In most of the proposed maintenance models it is generally assumed that spares are always available when needed for replacement, which is not usually the case in practice. In fact, since the procurement leadtime is generally non-negligible, any replacement policy should be combined with an appropriate ordering policy for timely supply of spare parts. In such cases, spare parts demand is governed by the failure mechanism of the operating units as well as by the applied preventive maintenance or replacement policy, if any. Thus, spare parts demand is usually more peculiar than that of regular products but, at the same time, manageable to some extent since preventive maintenance times are rather easily adaptable. In addition, shortage costs of spare parts are generally considerably higher than those of regular products since shortage of spares upon need may result in excessive production downtimes. Thus, typical inventory control models are generally not appropriate for spare parts management and ad hoc ordering policies have been proposed for such cases.

In practice, the problem of managing spare parts appears in several variations depending on the deterioration mechanism of the operating system, the number of operating parts, the type of the applied maintenance policy, the severity and detectability of failures and the limitations and special characteristics of ordering policies themselves. Therefore, the research on this field may take several directions to keep up with industry requirements. A thorough review on joint maintenance and inventory optimization models has been recently published by Van Horenbeek, Bure, Cattrysse, Pintelon, and Vansteenwegen (2013).

The study in the current paper was motivated by the spare parts inventory control and maintenance problem observed for steam traps in an oil-refinery. Steam traps are subject to non-observable failures which result in excessive losses of live steam. Thus, all traps are periodically inspected using a specialized monitoring device, which detects steam leaks through temperature and ultrasonic measurements analysis. According to the inspection outcome, traps may be preventively maintained, repaired or replaced by new ones. Clearly, the length of the inspection interval directly affects the cost incurred due to steam losses as well as the number of spares needed at every inspection instance. Considering that there are more than 3000 traps in the steam network of the company, it is clear that the decisions on the inspection frequency as well as on the ordering policy of spares are of major importance to the company. Therefore a joint maintenance and spare parts ordering policy is proposed and the economically optimal inspection interval, spare parts ordering time and quantity are derived.

The rest of the paper is structured as follows. In the next section the relevant literature is reviewed and briefly discussed. In Section 3 the problem setting as well as the proposed maintenance and ordering policies are described in detail. In Section 4 two models, differing in the type of the proposed ordering policy, are developed, while in Section 5 an extension of the proposed models is discussed. In Section 6 the proposed models are optimized for real case data, their economic performance against simpler approaches

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is investigated and a sensitivity analysis is performed. Section 7 summarizes the paper and presents topics for future research.

2. Literature review

The literature review presented in this section focuses on models that study spare parts ordering and maintenance policies taking into account the failure time distribution of the operating units. An important distinguishing characteristic of these models is whether they consider a single or several identical operating units. In fact, most of the proposed models assume a single operating unit and the great majority of them are restricted in the case of a single spare part in stock, as well. The objective is to derive the optimal ordering and replacement times that minimize the total inventory and maintenance cost.

Within this context, Wiggins (1967) derives the optimal ordering time for exponential failure times and corrective replacement assuming one spare in stock at most. The use of the exponential lifetime distribution leads to an extreme ordering policy, which dictates either immediate order of a new spare as soon as the one in stock is used or no order until a failure occurs and no spare is available. Osaki (1977) derives the optimal ordering time assuming that the operating unit is replaced as soon as the ordered spare is delivered or at failure, whichever occurs first. Thomas and Osaki (1978) investigate more general ordering – replacement policies allowing for emergency orders in case a failure occurs and no spare is available. Park and Park (1986b) study the same problem as in Thomas and Osaki (1978) assuming random leadtime but emergency orders are not allowed. As a result they conclude that the optimal replacement policy is extreme and similar to that studied by Osaki (1977). Armstrong and Atkins (1996) extend the analysis of Thomas and Osaki (1978) assuming that preventive replacement is generally less expensive than failure replacement. Other extensions of the model proposed by Thomas and Osaki (1978) are also studied in Dohi, Kaio, and Osaki (1998) and Giri, Dohi, and Kaio (2005).

Osaki, Kaio, and Yamada (1981), Park and Park (1986a), Sheu and Liou (1994), Sheu (1999) and Park and Sun (2009) consider two types of failures, a minor and a major one, and assume that minor failures are corrected by minimal repair actions. Chien (2010) also considers two types of failures and two types of corrective maintenance actions (minimal repair against minor failures and replacement against major ones) combined with preventive replacement and derives the optimal number of minimal repairs before ordering a spare part. Cheng and Li (2012) study a similar problem but they also derive the optimal number of minimal repairs prior to preventive replacement. Elwany and Gebraeel (2008) and Louit, Pascual, Banjevic, and Jardine (2011) extend the work of Armstrong and Atkins (1996) and study a Condition Based Maintenance (CBM) policy updating the lifetime distributions based on data obtained through condition monitoring. A CBM policy is also studied by Rausch and Liao (2010) who assume that maintenance is performed as soon as degradation exceeds a certain threshold. Rausch and Liao (2010) relax the assumption of a single spare part in stock and investigate a more general $(S-1, S)$ policy.

The assumption of a single spare part in stock is also relaxed in Falkner (1968), Nosoohi and Hejazi (2011), Kabir and Al-Olayan (1994), Dohi, Shibuya, and Osaki (1997) and Diallo, Aït-Kadi, and Chelbi (2008). More specifically, Falkner (1968) uses dynamic programming techniques to derive the optimal initial inventory, maintenance times and reorder quantities for the finite horizon case. Nosoohi and Hejazi (2011) develop a multi-objective model to derive an efficient solution for the age-based preventive replacement time and the initial stock of spare parts for a given planning horizon. Kabir and Al-Olayan (1994) use simulation to investigate a continuous review (s, S) policy combined with age-based preventive replacement, allowing for emergency orders in case of shortage. Dohi et al. (1997) study both periodic and continuous review policies, which combine regular and emergency orders. They derive the optimal ordering time and reorder quantity assuming that only corrective replacement is performed. Diallo et al. (2008) derive the optimal continuous review (s, Q) policy assuming that the operating unit is replaced upon order delivery or at failure, whichever occurs first.

The case of more than one identical units that operate in parallel is significantly harder to model and, therefore, the relevant research is rather limited. In addition, due to the mathematical complexity of the integrated ordering and maintenance problem for several operating units, most of the published works in the field either adopt a simple maintenance and/or ordering policy or use simulation to compute the cost of the proposed models.

More specifically, Allen and D'Esopo (1968) as well as Al-Bahi (1993) derive the optimal (s, Q) policy assuming exponentially distributed failure times and thus only corrective replacement is considered. On the other hand, Kabir and Al-Olayan (1996), Hu, Yue, and Xie (2008) and Kabir and Farrash (1997) investigate age-based preventive replacement combined with continuous review (Hu et al., 2008; Kabir & Al-Olayan, 1996) or periodic review (Kabir & Farrash, 1997) ordering policy, but they all resort to simulation in order to solve the problem. Acharya, Nagbhushanam, and Alam (1986), Brezavšček and Hudoklin (2003) and Huang, Meng, Xi, and Liu (2008) consider block replacement policies combined with periodic review ordering and assume that the stock review interval is equal to the block replacement interval. Block replacement is also examined by Sarker and Haque (2000), who consider a continuous review (s, S) ordering policy combined with expedited orders in case of zero spares in stock and use simulation to optimize their model. Vaughan (2005) derives the optimal ordering policy for periodically inspected operating units, a random number of which may be preventively replaced at inspection intervals. He assumes exponentially distributed failure times and uses dynamic programming to conclude that the optimal ordering policy is of the (s, S) type, where the reorder point s and the order-up-to level S depend on the time until the next inspection point. Wang (2011, 2012) derives both the optimal ordering parameters and inspection interval for periodically inspected components under the so called "Delay-Time" concept, according to which the failure is assumed to be a two-stage process. All failed components are correctively replaced upon failure while all defective components are preventively replaced upon inspection. Wang, Pecht, and Liu (2012) develop both theoretical and simulation-based models for spare parts ordering and maintenance decisions of systems equipped with early failure warning devices.

In the field of Condition Based Maintenance Li and Ryan (2011) use dynamic programming to derive the optimal inventory control policy assuming Brownian deterioration, control limit maintenance policy and periodic review of spare parts inventories. In addition, Xie and Wang (2008) and Wang, Chu, and Mao (2008, 2009) investigate joint Condition Based Maintenance and continuous review (s, S) ordering policies using simulation. Wang et al. (2008) investigate the optimal ordering parameters assuming non-observable failures, Markovian deterioration and control limit replacement policy. In Xie and Wang (2008) and Wang et al. (2009) failures are immediately detected and the optimal inspection interval and deterioration threshold are also investigated.

Although the current study shares some common features with previous works cited above, its main contribution is that it examines the joint maintenance – spare parts inventory problem for the multiple items case adopting an analytical approach, while most previous studies resolve to simulation for equally complex (or even