ARTICLE IN PRESS
JID: EOR [m5G;November 21, 2015;13:44]

European Journal of Operational Research 000 (2015) 1–10

Contents lists available at ScienceDirect

European Journal of Operational Research

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

Decision Support

Clustering condition-based maintenance for systems with redundancy and economic dependencies

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A R T I C L E I N F O

Article history:
Received 23 March 2015
Accepted 4 November 2015
Available online xxx

Keywords:
Reliability
Maintenance
Redundancy
Economic dependencies
Dynamic programming

A B S T R A C T

Systems that require maintenance typically consist of multiple components. In case of economic dependencies, maintaining several of these components simultaneously can be more cost efficient than performing maintenance on each component separately, while in case of redundancy, postponing maintenance on some failed components is possible without reducing the availability of the system. Condition-based maintenance (CBM) is known as a cost-minimizing strategy in which the maintenance actions are based on the actual condition of the different components. No research has been performed yet on clustering CBM tasks for systems with both economic dependencies and redundancy. We develop a dynamic programming model to find the optimal maintenance strategy for such systems, and show numerically that it can indeed considerably outperform previously considered policies (failure-based, age-based, block replacement, and more restricted (opportunistic) CBM policies). Moreover, our numerical investigation provides insights into the optimal policy structure.

1. Introduction

Maintenance costs can constitute up to 60 percent of the production costs of manufacturing firms, of which one third may be due to unnecessary or poorly executed maintenance (Mobley, 2002). For this reason, a lot of research has been developed in the field of maintenance strategies over the past decades, e.g. McCall (1965); Thomas (1986); Wang (2002), aiming to determine the right moment for performing maintenance. Whereas failure-based maintenance is always performed too late, i.e., after a failure has occurred, preventive maintenance strategies such as block replacement or age-based maintenance are typically too conservative, as they tend to schedule maintenance more often than required. Condition-based maintenance (CBM) can be a more efficient strategy, as it postpones maintenance activities where possible while limiting failures due to constant monitoring of certain conditions, such as vibration and temperature (Gertsbakh, 1977; 2000). Nevertheless, most of the existing research focuses on preventive maintenance policies rather than CBM.

Most contributions develop maintenance policies for simple systems consisting of a single unit (Wang, 2002). However, the simplicity of these models compared to the complex reality may be one of the factors explaining the lack of success in applications of maintenance policies (Van der Duyn Schouten, 1996), which is why research is shifting more and more to realistic systems that contain multiple components. Literature reviews on maintenance policies for multi-unit systems are given by Cho and Parlar (1991); Dekker, Wildeman, and van der Duyn Schouten (1997); Van der Duyn Schouten (1996); McCall (1965); Thomas (1986); Wang (2002). Again, most of this research focuses on preventive maintenance rather than on CBM.

When dealing with multi-unit systems, three types of dependencies can exist: economic dependence, structural dependence, and stochastic dependence. Applying a single-unit model to a multi-unit maintenance problem is only optimal if none of these dependencies applies (Cho & Parlar, 1991). In this paper, we focus on economic dependencies, which means that combining maintenance actions can yield a lower total cost than maintaining each component separately (Castanier, Grall, & Bérenguer, 2005). This is for example the case when fixed set-up costs need to be paid, which are independent of the number of components that require maintenance. Economic dependencies are very common in most continuous operating systems, such as aircrafts, powerplants, or chemical processing facilities (Wang, 2002). Combining maintenance on different components is also known as clustering or opportunistic maintenance. There is often a great cost saving potential by implementing an opportunistic maintenance policy for multi-unit systems with economic dependencies (Wang, 2002).

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http://dx.doi.org/10.1016/j.ejor.2015.11.008

Nomenclature

δ_i	Binary variable indicating whether or not a replacement (preventive or corrective) should be performed on component i
μ_i	Deterioration parameter of component i
c_c^i	Cost of a corrective replacement on component i
c_p^i	Cost of a preventive replacement on component i, $c_p^i < c_c^i$
c_s	Fixed set-up cost for maintenance
C_t	Optimum cumulative cost from period t on
f_i	Pdf of the deterioration increments of component i
k	Number of components in the system that need to function for the system to function
L_i	Fixed failure level of component i
N	Number of components in the system
p	Penalty for a system failure
$R(x_1, x_2, \ldots, x_N)$	System reliability, given deterioration levels of $x_1, x_2, \ldots, x_N$ for components $1, 2, \ldots, N$, respectively
$R_i(x_i)$	Reliability of component i, given a deterioration level of x_i
S_N	Set of all component labels, $S_N := \{1, 2, \ldots, N\}$
X_t^i	Condition of component i at time t, $X_0^i = 0$
$\bar{X}_t^i$	Condition of component i after possible maintenance has been performed
Y_t^i	Increase in deterioration on component i during t, $X_{t+1}^i = \bar{X}_t^i + Y_t^i$

In practice, many multi-unit systems employ redundancy, which is the most common approach to increase availability and prevent downtime of the equipment (Moghaddass, Zuo, & Pandey, 2012). Consider for example a gas distribution company that has plants with redundant pumps to distribute gas, to ensure a continuous operation of the system and to prevent that clients will be without gas. A well-known type of redundancy in systems with spares or in so-called fault-tolerant systems is the k-out-of-N system, which has wide applications in both industrial and military systems (Kuo & Zuo, 2003). A k-out-of-N system is a system consisting of N components which functions as long as at least k components function. Many settings can be viewed as special cases of the k-out-of-N system; the 1-out-of-N system represents a parallel system (fully-redundant), the N-out-of-N system represents a series system (non-redundant), and the k-out-of-N system with $1 < k < N$ is also known as a partially-redundant system (Boland & Proschan, 1983; Misra, 2012).

While scheduling maintenance, systems with redundancy have the unique property that the system could still function even if some components have failed. Hence, failed components do not always require immediate replacement. In case of economic dependencies, it might be cheaper to postpone the maintenance until other components require maintenance as well. Of course, doing so does increase the risk of down-time as (some of) the remaining units also fail unexpectedly. Obviously, condition monitoring could reduce that risk, but CBM has so far not been considered for multi-unit systems with economic dependencies and redundancy. To the best of our knowledge, this paper is the first to do so.

The remainder of this article is organized as follows. In Section 2, a short overview of relevant literature is given. Section 3 describes the system under investigation. Section 4 explains the dynamic programming model used to optimize the maintenance policy. In Sections 5 and 6, results of a numerical investigation are presented, describing the optimal policy and comparing it to classical policies. Section 7 concludes the paper.

2. Literature review

Many authors have considered one or more of the following elements: CBM, redundancy, or economic dependencies. Fig. 1 gives a schematic overview of the types of systems considered. Although the figure is intended as an illustration, all articles are included that combine at least two of the elements. Interestingly, there is just a single study on CBM for systems with redundancy (Lu & Jiang, 2007). Moreover, this study does not consider economic dependencies, as we do.

Examples of articles that consider corrective or preventive maintenance policies for systems with redundancy, in the form of k-out-of-N systems, are given by Bjarnason, Taghipour, and Banjevic (2014); Park and Pham (2012); de Smidt-Destombes, van der Heijden, and van Harten (2004); 2006); 2007); 2009). In fact, failure-based maintenance is considered in Bjarnason et al. (2014), while block replacement is studied in Park and Pham (2012); de Smidt-Destombes, van der Heijden, and van Harten (2007). Both de Smidt-Destombes, van der Heijden, and van Harten (2009) and de Smidt-Destombes et al. (2004) study purely corrective maintenance that is initiated as soon as the number of failed components exceeds some critical level, while in de Smidt-Destombes, van der Heijden, and van Harten (2006) both failed and degraded components are replaced at those times. An example of an article that is only focused on CBM is given by Wang, Chu, and Mao (2009), in which a preventive replacement threshold is considered for a multi-unit system. So far, CBM has only been considered for a system with redundancy in Lu and Jiang (2007), where failure-based maintenance, time-based maintenance, and CBM with a preventive replacement threshold are compared for a k-out-of-N standby system without economic dependencies.

In Dekker et al. (1997), a literature review on maintenance policies for multi-unit systems with economic dependencies is given. An example of a preventive replacement policy developed for a multi-unit series system with economic dependencies is that by Zhou, Xi, and Lee (2009), while CBM policies are considered for a two-unit series system with economic dependencies by Barbera, Schneider, and Watson (1999); Castanier et al. (2005). Furthermore, maintenance actions are grouped based on condition-monitoring information for a multi-unit system with economic dependencies in Bouvard, Artus, Bérenguer, and Cocquempot (2011), and a CBM policy with risk-thresholds for preventive and opportunistic replacements is considered for a multi-unit system with economic dependencies in Tian and Liao (2011). Finally, an article that considers systems with different structures (including k-out-of-N) and economic dependencies is given by Vu, Do, Barros, and Bérenguer (2014), in which periodic age-based maintenance actions are grouped.

To our knowledge, despite the widespread presence in industry of systems with both redundancy and economic dependencies, no research has been performed on CBM for such systems. We will cover this gap by developing a dynamic programming model to optimize the CBM policy for a k-out-of-N system with economic dependencies. An advantage of applying dynamic programming for this explorative study is that the structure of the optimal policy can be explored (numerically) and compared to commonly used strategies. Previously, dynamic programming has also been applied in, for example, Barbera et al. (1999); Zhou et al. (2009).

3. System description

3.1. Deterioration model

We consider a k-out-of-N system, defined here as a system consisting of N (nonidentical) components that functions as long as at least k components function ($1 \le k \le N$). All functioning components