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Decision Support

Joint condition-based maintenance and inventory optimization for systems with multiple components

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Efficient (condition-based) maintenance planning and inventory control of spares for critical components jointly determine the effectiveness of a maintenance strategy and, thereby, balance system uptime and maintenance costs. Duplicating an optimal policy for a single-component system to a multi-component system is not necessarily optimal, while a separate or sequential optimization of the maintenance and inventory decisions is also not guaranteed to yield the lowest costs. We therefore consider the joint optimization of condition-based maintenance and spares planning for multi-component systems. We formulate our model as a Markov Decision Process, and minimize the long-run average cost per time unit. A key insight from our numerical results is that the (s, S) inventory policy, popular in theory as well as practice, can be far from optimal for systems consisting of few components. Significant savings can be obtained by basing both the maintenance decisions and the timing of ordering spare components on the system's condition.

1. Introduction

Unexpected failures and resulting downtime account for large losses in the productivity and profitability of a firm (Alsyouf, 2007). Effective maintenance policies can reduce equipment downtime substantially, but rely heavily on the availability of spare components (Jiang, Chen, & Zhou, 2015). Consequently, the joint optimization of maintenance and inventory decisions is an important research area, but most of the existing research, discussed next, considers either maintenance or inventory planning rather than the interface (Van Horenbeek, Scarf, Cavalcante, & Pintelon, 2013). We remark that the (service logistics) inventory literature often uses the term "spare part", whereas it is common in the maintenance literature to refer to "components" rather than "parts". To avoid confusion, we will use "spare component" or the shorter "spare" in this paper.

Regarding maintenance decisions, many types of maintenance policies have been both employed in practice and extensively studied under various circumstances, such as corrective, periodic, age-based, and condition-based maintenance (CBM) (Wang, 2002). Compared to other maintenance policies, CBM can be more efficient (Gertsbakh, 1977; 2000), since it bases the maintenance actions on the actual system state. It can reduce the number of failures (thereby lowering downtime), minimize maintenance costs, and improve operational safety (Rao, 1996). For instance, a CBM policy has been developed for multi-component systems subject to both redundancy and economic dependencies in Olde Keizer, Teunter, and Veldman (2016), without considering inventory decisions. For literature reviews on maintenance policies, we refer to Van der Duyn Schouten (1996), Dekker, Wildeman, and van der Duyn Schouten (1997), Wang (2002). In particular, CBM has been considered by van Noortwijk (2009), Ahmad and Kamaruddin (2012), Bousdekis, Magoutas, Apostolou, and Mentzas (2015), Marseguerra, Zio, and Podofillini (2002), Hong, Zhou, Zhang, and Ye (2014), Li, Deloux, and Dieulle (2016), Rasmekomen and Parlikad (2016). Also inventory strategies have been extensively researched, of which reviews are provided by Kennedy, Wayne Patterson, and Fredendall (2002), Basten and van Houtum (2014), van Houtum and Kranenburg (2015). The spares inventory literature typically treats demand as given, thereby ignoring the underlying maintenance planning, while the majority of research on maintenance assumes an unlimited number of spares. Relatively few contributions exist on the joint optimization of maintenance and inventory. Next, we only discuss those that consider CBM, and refer interested readers to more in-depth reviews in Van Horenbeek, Buré, Cattrysse, Pintelon, and Vansteenwegen (2013), Pierskalla and Voelker (1976), Cho and Parlar (1991).

When considering a joint CBM and inventory policy for a system consisting of a single component, it is proven that a so-called monotonic policy structure is optimal (Kawai, 1983). In such a

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Nomenclature

δ_j	binary variable indicating whether or not component j is replaced
μ_j	deterioration parameter of component j
ω	decision variable indicating how many spares to order
c_r^j	cost of a replacement on component j
F	fixed cost per order
H	holding cost per spare per time unit
L_j	fixed failure level of component j
O^j	vector with operating costs for different states of component j
P^j	transition probability matrix of component j
R^j	vector with replacement costs for different states of component j
S	maximum stock level
s	reorder stock level
$\bar{S}$	maximum inventory position
s_h	number of spares on hand
s_l	number of spares ordered l time units ago
T	fixed lead time, $T > 1$
x_j	state of component j

policy, deterioration thresholds are used to determine when to order a spare and, upon arrival of the spare, when to replace the component. Other examples of sequential or joint optimization of CBM and the spares inventory for a single-component system are given by Kawai (1983), Elwany and Gebraeel (2008), Wang, Chu, and Mao (2008a), Rausch and Liao (2010), Louit, Pascual, Banjevic, and Jardine (2011), Zhao and Xu (2012).

In practice, systems often contain multiple components. Applying a single-component policy to such a multi-component system is generally far from optimal for several reasons (Cho & Parlar, 1991). First, different types of dependencies can exist in multi-component systems, which can be economic, structural, or failure-related (Thomas, 1986). In such cases, the optimal maintenance and inventory decisions depend on the complete system state rather than on a single component. Second, multiple components can share a set of identical spares. We remark that identical components may have different failure rates as they can for instance be contained in subsystems that operate under different conditions. Examples are systems consisting of multiple production lines with similar critical components (such as conveyor belts), or gas treatment facilities that use multiple relatively similar pumps to ensure a continuous gas distribution. Obviously, the right number of shared (or pooled) spares should be determined at the system level. It is well known from the inventory pooling literature (see, e.g., Guajardo, Rönnqvist, Halvorsen, & Kallevik, 2015; Karsten & Basten, 2014) that a decomposed approach at the component level leads to much higher inventory levels and costs.

To the best of our knowledge, the integration of CBM and inventory for multi-component systems has only been studied by Wang, Chu, and Mao (2008b), Xie and Wang (2008), Wang, Chu, and Mao (2009), Van Horenbeek and Pintelon (2015). Whereas a shared pool of spares is considered in Wang et al. (2008b), Xie and Wang (2008), Wang et al. (2009), economic and structural dependencies are included in Van Horenbeek and Pintelon (2015). A sequential optimization of maintenance and inventory is considered in Van Horenbeek and Pintelon (2015). However, separate or sequential optimization of maintenance and inventory actions will not necessarily lead to a globally optimal policy (Xie & Wang, 2008). For this reason, maintenance and inventory decisions are jointly optimized in Wang et al. (2008b), Xie and Wang (2008), Wang et al. (2009). All three papers consider an (s, S) inventory policy, which means that an order is placed to refill the inventory position to S units once it drops below s. It is well-known that the order level, order-up-to level (s, S) policy is optimal under quite general conditions for inventory systems (Iglehart, 1963; Sahin, 1990; Scarf, 1959). This policy has also been considered by many authors for controlling spare part inventories (e.g., Cohen, Kleindorfer, Lee, & Pyke, 1992; van Jaarsveld, Dollevoet, & Dekker, 2015; Kennedy et al., 2002; Kranenburg & van Houtum, 2009; Strijbosch, Heuts, & van der Schoot, 2000; Svoronos & Zipkin, 1991; Williams, 1984; Zohrul Kabir & Al-Olayan, 1996). In practice, this policy is often referred to as the min–max policy, where an order is placed up to the maximum if the inventory position drops to (or below) the minimum. This policy is available in all major software packages for stock control (e.g., Slimstock) or Enterprise Resource Planning (e.g., SAP). Intuitively, however, components only need to be replaced and thus require a spare when they are close to failure. The condition information that is used for scheduling maintenance can thus also be used for deciding when to order spares. No research has been performed yet on this (just-in-time) condition-based ordering for multi-component systems, despite the obvious cost savings potential. To cover this gap, we are the first to consider the joint optimization of the condition-based maintenance and inventory decisions for a multi-component system with a shared pool of spares. We benchmark the performance of our condition-based inventory policy against that of an (s, S) policy and the optimal policy for a single component. Another contribution is that we are the first to provide an exact method for a multi-component system by formulating the problem as a Markov Decision Process, whereas Wang et al. (2008b), Xie and Wang (2008), Wang et al. (2009) use a simulation-based approach. In this way, we are able to obtain structural insights through a numerical study. Many Markovian maintenance models have been developed for deteriorating single-component systems, e.g., Byon, Ntaimo, and Ding (2010), Elwany, Gebraeel, and Maillart (2011), Ulukus, Kharoufeh, and Maillart (2012), Borrero and Akhavan-Tabatabaei (2013).

The remainder of this paper is organized as follows. Section 2 gives a description of the system, while we formulate the model as a Markov Decision Process in Section 3. Next, we present a numerical study and comparison to the (s, S) policy for a two-component system in Section 4, followed by a sensitivity analysis in Section 5. In Section 6, we consider a system with more than two components. Section 7 concludes the paper.

2. System description

2.1. Model description

To obtain structural insights, we consider a discrete-time system consisting of N components, which function and deteriorate independently. We model the condition of a component j, $j = 1, 2, \ldots, N$, discretely using $L_j + 1$ different states, $0, 1, \ldots, L_j$, where state 0 means that the component is as-good-as-new, and state L_j means that the component has failed. The components share a pool of spares. Although the components are identical, they may be contained in different subsystems that may operate under different conditions, possibly leading to different failure rates. If a component is replaced, the old component is discarded, and the new component is in the as-good-as-new state 0. Since repair times are typically small (days) compared to the expected lifetime of a component (years) and lead times of spares (months), replacements are assumed to be instantaneous, but can only be scheduled if the required spares are on hand. Spares can be ordered in any amount, and arrive after a fixed lead time of T time units (typically in the order of months). After possible maintenance and inventory actions have been performed, component j is subject to deterioration. We assume that deterioration worsens, rather than improves,