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Joint optimization of redundancy level and spare part inventories

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ABSTRACT

We consider a "k-out-of-N" system with different standby modes. Each of the N components consists of multiple part types. Upon failure, a component can be repaired within a certain time by switching the failed part by a spare, if available. We develop both an exact and a fast approximate analysis to compute the system availability. Next, we jointly optimize the component redundancy level with the inventories of the various spare parts. We find that our approximations are very accurate and suitable for large systems. We apply our model to a case study at a public organization in Qatar, and find that we can improve the availability-to-cost ratio by reducing the redundancy level and increasing the spare part inventories. In general, high redundancy levels appear to be useful only when components are relatively cheap and part replacement times are high.

1. Introduction

In maintenance logistics, it is well known that unplanned downtime of advanced capital equipment can yield safety hazards, and may also be extremely expensive. For example downtime of an average aircraft is estimated as about $10,000 per hour and for a high-tech lithography system in the semiconductor industry it costs about $100,000 per hour. Consequently, unplanned downtime should be avoided, e.g. by exploiting advanced condition monitoring techniques, built-in redundancy and preventive maintenance policies. Further, one should quickly restore a system upon failure, which can be done by switching a failed lower-level part by a spare, if available on-site. In this paper, we concentrate on the trade-off between avoiding downtime using an adequate redundancy level, and quick system restore using adequate inventories of lower-level spare parts. We encountered this issue at a central chilling facility with built-in redundancies for a public company in Qatar.

The analyzed system consists of six centrifugal pumps that are compressing the chilling agent for further usage in the central air-conditioning system. These pumps (components) can be switched on or off depending on their availability and current weather conditions; however, only three pumps are required for the full scale operation. Each of the components (pumps) can fail due to a malfunctioning lower-level part. A service engineer repairs the component by replacing this part by a spare one from local stock, if available (Fig. 1). Part replacement requires some time during which the pump is not available. The stock of the spare parts is replenished later on from a central stock or from an external supplier. Although the facility has almost double capacity, the system availability at full required capacity is 92% only due to long replenishment lead times and lack of spare part stock. This raises the question to which extent stocking spare parts could contribute to an increase in system availability, possibly in combination with a reduction of the redundancy level.

We can encounter similar situations where continuous operation is essential, such as hospitals, transportation networks, telecommunication, etc. In such cases, the continuous operation can be ensured by having available a set of large and expensive components (transformers, generators, switches, etc.) that form a reliable structure at reasonable costs.

In the next section, we will position our research in the literature and discuss our contribution. In Section 3, we state our model and notation, and we formulate the continuous-time finite-state Markov chain that is the basis of our analysis. We show how we can exactly evaluate the system availability for a given number of installed components and given initial stock levels for the spares in Section 4. As this method is slow for large systems because of the rapidly expanding state space, we also derive an approximate method in the same section. Section 5 deals with the joint optimization of the component redundancy level and the spare part inventory level. We validate our approximations by

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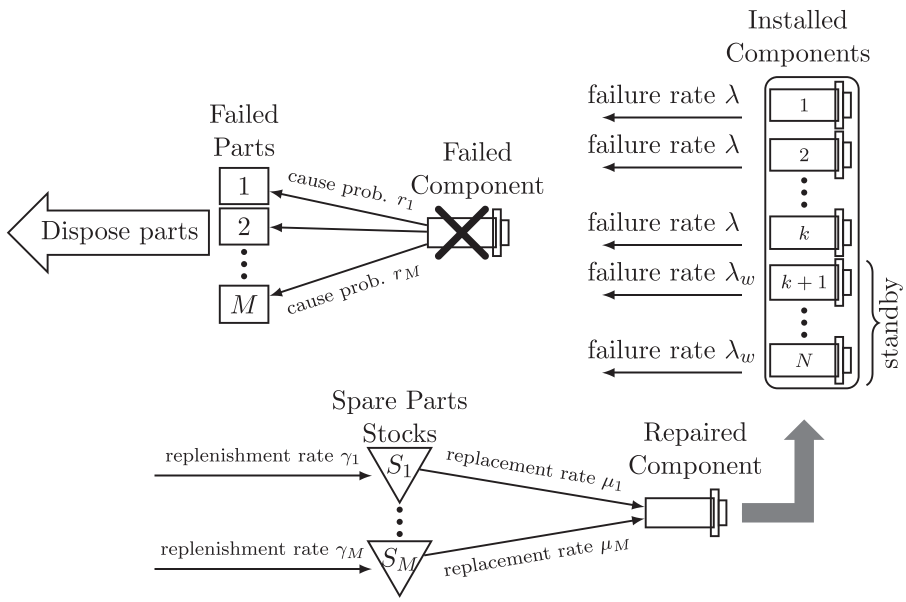

Fig. 1. The failure-repair process in the presented k-out-of-N system.

comparison to results of discrete event simulation in Section 6. Also, we provide insights in the trade-off between the redundancy level and spare part inventories in presence of significant replacement times. In Section 7, we give our key conclusions, and discuss possible model extensions for other redundancy structures and directions for further research.

2. Literature review

A common way to increase the reliability of equipment is by redundancy for critical components, as is done currently in military, aviation, oil/gas industry and many other applications [12]. The literature on the analysis of redundant systems, including the optimization of redundancy levels, is abundant, see e.g. Zhang and Chen [30] and their references.

Spare part inventory management also has a long history in research, with the work of Sherbrooke [21] as key reference. Costantino et al. [7] presented how classical spare parts inventory models (VARI-METRIC) are applied to the Italian Air Force. Barabadi et al. [2] focused on spare part demand forecasting, taking into account operating conditions of the systems, modeled as covariates. For a recent overview of research progress in spare part inventory management, we refer to Basten and Van Houtum [3].

Many works addressed integrating aspects of reliability and maintenance logistics into one model. One stream of research relates maintenance planning to spare part inventory management, e.g. Wang et al. [28], Wang [27], Van Horenbeek et al. [25], Jin et al. [16]. Godoy et al. [14] used condition information to order spare parts rather than stocking them. Godoy et al. [15] developed a framework to decide upon outsourcing a spare part pool under age-based maintenance. We refer to Van Horenbeek et al. [24] for a recent review of papers on such joint optimization models.

Considerably less work has been done on the integration of system redundancy with spare part inventories. Most research focuses – in contrast to our work – on a single part type only. Fawzi and Hawkes [13] is one of the first papers in this area. De Smidt-Destombes et al. [8–10] considered a k-out-of-N system of a single part type supported by spares for different failure behaviors, replacement strategies, and repair capacities. They focused on relatively large values of N (100). Chakravarthy and Gómez-Corral [5] considered a single k-out-of-N system with spare part delivery times and a single repair man. The spare part inventory level is not a decision variable. Van Jaarsveld and Dekker [26] used reliability centered maintenance data to optimize spare part inventories for a redundant system with a deterministic replacement time. Selçuk and Ağralı [20] analyzed a system where each part is critical for the functionality of the whole system, and emergence supply is applied if replacement parts are not available in stock. Xie et al. [29] considered the joint problem of redundancy allocation and inventory optimization of repairable spare parts for k-out-of-N hot standby systems in series, with a single server repair shop and strictly positive replacement times for the spare parts. Bjarnason et al. [4] analyzed a k-out-of-N system with hidden failures, and jointly optimized the inspection frequency and the spare part inventory. Jin et al. [17] considered multiple hot standby redundant systems with shared standby components and spares. They showed the advantages of sharing redundant components between systems.

Less research has been conducted on multi-item models. In [21, ch.6] a system with hot standby redundancy at both component and part level is described, where spare parts are periodically resupplied. Cochran and Lewis [6] modified this model for a small installed base in which the arrival process of parts is significantly influenced by the number of systems being operational. De Smidt-Destombes et al. [11] considered a multi-item, single site spare part optimization problem for k-out-of-N systems with cold standby redundancy and negligible component replacement times. They minimize the spare part investment given a target value for the mission reliability with fixed mission length T. Sahba et al. [19] studied the impact of dedicated versus pooled spare part inventories as well as dispatching rules for repaired parts for multiple k-out-of-N systems consisting of a single part type. Installation times are zero in their model.

Our model is different from the models described above in four main aspects. First, we allow component failures due to multiple lower-level part types installed in the system, whereas we have seen that most other papers are restricted to a single part type. Second, we assume that the system failures rate depends on the number of the components in the operating and in different standby modes, whereas Sherbrooke [21] and De Smidt-Destombes et al. [11] assume a constant system failure rate. Third, we allow for different (and even mixed) standby modes, which affects the failure rates and complicates the analysis of the