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Spare parts stock control for redundant systems using reliability centered maintenance data

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ABSTRACT

In the classical approach to determine how many spare parts to stock, the spare parts shortage costs or the minimum fill rate is a key factor. A difficulty with this approach lies in the estimation of these shortage costs or the determination of appropriate minimum fill rates. In an attempt to overcome this problem, we propose to use the data gathered in reliability centered maintenance (RCM) studies to determine shortage costs. We discuss the benefits of this approach. At the same time, the approach gives rise to complications, as the RCM study determines downtime costs of the underlying equipment, which have a complex relation with the shortage cost for spare parts in case multiple pieces of equipment have different downtime costs. A further complication is redundancy in the equipment. We develop a framework that enables the modeling of these more complicated systems. Based on the framework, we propose an approximative, analytic method that can be used to determine minimum stock quantities in case of redundancy and multiple systems. In a quantitative study we show that the method performs well. Moreover, we show that including redundancy information in the stocking decision gives significant cost benefits.

1. Introduction

Availability of spare parts is important for companies, because spares are needed for efficient operation of capital goods. When equipment breaks down, the downtime can be significantly reduced if all spares needed for the repair are immediately available. If on the other hand spares are not immediately available, the waiting time for the spares can cause costly production losses. Because the costs of keeping spare parts on stock can be high, it is not obvious whether we should keep stock—either how many—to avoid downtime, or whether we should refrain from keeping stock to avoid holding costs. It is apparent from overviews of spare parts inventory control [1,2] that most models aiming to support inventory decisions assume that certain pieces of information regarding the spare parts are available. Such pieces of information include the price and leadtime of the spare part, the usage frequency of the part, and the shortage costs that are incurred during the waiting time for the part. Especially the shortage costs and, in cases without demand history, the usage frequency, are hard to estimate in practice. A method to circumvent the former problem is the setting of so-called service level targets, but finding appropriate values for these targets may prove difficult as well.

The research we report on was performed at a large petrochemical company. When determining stock quantities, obtaining reasonable estimates for the shortage costs was troublesome because of lacking data.

The company carries out reliability centered maintenance studies in order to improve maintenance practice at their plants. Reliability centered maintenance is a structured approach to ensure that all available data and knowledge is used to arrive at an optimal maintenance regime [3]. As part of the particular type of RCM study carried out by the company, the production loss incurred during equipment downtime, and the estimated frequency of occurrence of different failure modes are quantitatively determined. This data can be valuable to enhance inventory control, because the shortage costs for spare parts are clearly related to the downtime costs of the equipment.

While in inventory models often shortage costs consisting of a single number are assumed, in practice all equipment in which the spare part is used is a potential source of downtime costs. The downtime costs of similar pieces of equipment installed in different systems need not be equal. Another complication that came forward is redundancy. When there are two pieces of equipment, of which only one is needed to keep the plant running, a breakdown of one does not necessarily have severe economic consequences. In summary, the downtime costs cannot be trivially translated to shortage costs for the spare parts.

We contribute by proposing a new, versatile inventory model that can be used to tackle the above-mentioned complications resulting from the use of RCM data in inventory control. While the use of RCM data for spare part inventory control has to our best knowledge not been described in literature before, there are a number of contributions on spare parts inventory control for redundant systems.

In de Smidt-Destombes et al. [4] the trade-off between repair capacity and spare part inventory control is investigated for a

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single *k* out of *N* system under condition based maintenance; i.e. when the number of defect pieces of equipment exceeds some previously defined limit, maintenance is initiated. They propose exact and approximate methods to analyze the system availability. In a later paper [5] the possibility that pieces of equipment degrade before failing is included, which complicates the analysis significantly and allows for more refined policies. De Smidt-Destombes et al. [6] consider *M* identical *k* out of *N* systems under block replacement. For each system all defect pieces of equipment are replaced every fixed time interval. Two methods are proposed to analyze the system availability as a function of the number of spare parts stocked and the block replacement interval. Their most recent contribution [7] on the subject considers the optimization of the control parameters in the models presented earlier [4–6] to reach the target availability at minimal cost. Chakravarthy and Gómez-Corral [8] consider a single *k* out of *N* system, spare pieces of equipment, and a single repair man. When a piece of equipment fails, a spare part is requested with a given probability. A matrix analytic approach is used to evaluate the performance of these systems.

Our model differs significantly from the models mentioned above, and none is more general. The differences between the models result from a difference in application. In the application examples given for the studies by de Smidt-Destombes et al., initiating maintenance involves a major setup cost and a significant setup time, elements that are both incorporated in their model. Neither a setup cost nor a setup time plays a significant role for our application, and these were consequently not included in our model. Conversely, while the contributions mentioned above only consider a single system [4,5,8] or multiple identical systems [6,7], our model is very flexible in the sense that it allows an arbitrary combination of redundant systems, between which both the failure rate and the amount of redundancy may vary. The flexibility is needed to make the model applicable because practical cases may involve combinations of redundant systems with different redundancy levels and failure rates. Finally, our model is specifically designed to work with a detailed cost structure. It is therefore possible to model a system in which the throughput depends on the number of defect pieces of equipment in a gradual manner, another feature that is needed to make the model applicable for use with data coming from an RCM study.

Redundant systems play an important role in this research. Allocating redundancy during the design of systems is a well-studied problem, often referred to as the redundancy optimization problem (ROP). A number of variants have been studied, for a recent overview we refer the reader to Kuo and Wan [9]. We will review contributions that explicitly consider spare parts.

Nourelfath and Dutuit [10] study a variant with limited repair resources (e.g. repairmen/spare parts), which are shared over all subsystems. Both this model and the model we propose are in a sense multi-state systems, a difference being that in their model the reliability is included via the loss of load probability (LOLP), while we include the notion of reliability as state-dependent downtime costs. The LOLP is a meaningful and widely used measure of reliability during the design of systems. However, we will see that the latter approach is more suitable to optimize spare part inventory based on RCM data. Nourelfath and Dutuit propose a combination of the universal moment generating function in a genetic algorithm (GA) to find a good configuration for the system with infinite resources. This solution is used as a starting point to find a solution of the system with finite resources, which is found heuristically based on simulation.

Nourelfath and Ait-Kadi [11] study the same problem, except that they assume dedicated resources for each subsystem. For this case, the process of the different subsystems is no longer coupled by the resource. Based on this observation, they propose an analytic calculation of the downtime costs to replace the time consuming simulation in [10]. This approach is not usable in our setting, because spare parts are often shared across subsystems.

Cantoni et al. [12] consider the problem of optimizing the number of spare parts for redundant systems. Marseguerra et al. [13] extend this work to a multi criteria approach, using the notion of pareto-dominance. The solution methodology proposed in these works is based on a GA, and simulation is used to estimate the quality of solutions. They propose a so-called drop-by-drop approach to reduce the computational burden of simulation, a method that was later improved by Li and Li [14].

The use of simulation in these contributions allows for the use of a very detailed system model. It is argued [12,13] that, for cases with significant safety implications, such a detailed system model is in order. We concur with this view. Our focus will be on systems with less consequential (but still very costly) failures. As we will argue in Section 2.2, for such systems, a detailed system model is not cost effective, and a model that focuses on the most important aspects of the problem is more suitable. Moreover, computation time is a more important issue for such systems, implying that simulation is not the most appropriate optimization tool.

Based on the knowledge that a complex system model is not cost effective for the type of applications on which we focus, we propose a model for which the data requirements are more limited. The model still captures the most important problem aspects, such as redundancy and partial throughput.

To optimize the reorder point based on the model, we propose two analytic approximations of the downtime costs. We develop an algorithm that can be used to determine the optimal reorder points based on these approximative methods. In a numerical experiment, we show that the cost increase as a result of using one of the approximations is very small, and the cost increase of the other approximation is slightly larger, but this approximation is more intuitive to grasp. Both algorithms give results instantaneously, and additionally are considerably easier to implement than a simulation optimization approach.

Finkelstein [15] also considers spare parts for redundant systems, but only non-repairable systems are considered. A situation with a number of pieces of equipment in series is considered, each with spare equipment in cold standby. As the number of pieces of equipment in series goes to infinity, and under the assumption that the spares can be shared, it is proven that the survival function of the system converges to the step function. This result is extended to continuous resource sharing. Finally, results related to optimal switching are derived.

Another related work is the paper by Dekker and Plasmeijer [16]. They advocate setting quantitative estimates for unit downtime costs in complex systems in order to facilitate decision making both on maintenance and on spare parts inventory levels. They provide methods to estimate these downtime costs. We take a different perspective. We will not estimate the downtime costs of individual pieces of equipment but instead directly estimate the shortage costs of spares in the combined system.

As mentioned, one of our contributions lies in proposing a new inventory model capable to work with RCM data. We develop fast and accurate methods to find good reorder points using the model. Finally, we present quantitative evidence that the value of using the detailed RCM data is significant. In particular, we compare the costs of the proposed methods with the costs of more traditional methods, and find significant cost benefits of the former over the latter.

This work expands on an earlier contribution [17]. In the present work, we propose a new approximation with a significantly improved performance. We also add an extensive numerical experiment, from which many insights are derived.

The remainder of this paper is organized as follows. In Section 2 we give a description of the type of RCM study carried out at the