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A spare parts model with cold-standby redundancy on system level

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ABSTRACT

This paper presents a variant of a spare parts inventory model with cold stand-by redundancy on system level. Redundancy on system level implies that not all systems need to be operational in order to have the whole system operational. The cold stand-by feature implies that only the minimum required systems are operational. In order to determine a cost effective spare parts package such that in a cold stand-by redundancy situation a sufficient number of systems is operational for a specified period we extend the METRIC methodology. To compute the probability that the number of operating systems during the operational period is sufficient, we present both an exact, but time-consuming method, and a fast approximation method based on fitting distributions on the first two moments. This approximation method shows very small differences when compared to the exact method. Finally, we compare both methods to a simulation model in order to test the validity and impact of our modelling.

1. Introduction

Many of today's technological systems, such as aircraft or military installations are characterised by a high level of complexity and sophistication. The users of these capital assets usually require a guarantee of high availability, since the consequences of downtime can have very serious repercussions, e.g. economic loss or safety hazards. For example, in the case of military equipment downtime may lead to mission failure. In order to achieve a high level of availability it is often profitable to replace a failed component by a new one and restore the failed component off-line. In this way, the downtime of a system can be limited to the replacement time only. Obviously, spare parts are needed in order to perform such a maintenance rule and thus the number and the type of spare parts that are available influence the availability of a system. However, from a cost perspective it is important to purchase only the spares that are needed to achieve the required availability level, especially since the repairable items are often very expensive. Deciding which components to purchase and in what amounts in order to achieve the required availability level against the lowest possible costs is therefore an important question.

In the literature, a lot of attention is paid to spare parts inventory models designed to address this question. The simplest models are the models that are concerned only with the availability and do not take into account the costs, the so-called *item approach* models. These models decide per item what amount of spare parts is needed in order to achieve a certain availability level for that particular item. Silver et al. [1] look at single items or a group of items and these groups of items are categorised according to price, which gives the costs of the item at least some importance. The models that do take into account the cost of the spare parts are the so-called *system approach* models, which are studied rather extensively. Most of these models are based on a method called multi-echelon techniques for recoverable item control (METRIC), which was designed originally for the US Air Force by Sherbrooke [2]. This basic model considers a multi-item system consisting of one indenture level and two echelons. Since the appearance of this model, several extensions have been made concerning multi-indenture structures (see e.g. Muckstadt [3]), condemnation (see e.g. Simon [4]), lateral transhipments (see e.g. Dada [5] or Sherbrooke [6]) and commonality (see e.g. [14]).

A way to guarantee the required availability is the use of redundancy. In the case of military aircraft, usually a redundancy on system level has to be ensured to guarantee the required performance. Surprisingly enough, hardly any literature was found on the spare parts inventory optimisation of multi-item systems with system redundancy. In such a situation there are N identical systems of which only $k<N$ are needed for an acceptable functioning of the whole system. Such applications can be found in situations where it is (nearly) impossible to guarantee the required level of availability in another way, e.g. when a number of systems have to be operating on a location where during a certain amount of time re-supply is not possible. The best-known

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applications requiring system redundancy come from military (aircraft) situations, but Cochran and Lewis [7] mentioned several others, such as exploration, mining and rescue situations.

The encountered literature concerns the situation of hot stand-by redundancy, which is defined as: all the non-failed items are fully operational, including the ones that are not strictly needed. A detailed discussion can be found in Kaplan [8], Cochran and Lewis [7] and Sherbrooke [6]. Sherbrooke [6] developed a stockage model for a space station, where re-supply is periodic and only possible with a space shuttle flight. Redundancy is defined not only at system level, but also within a system at component level. In this case, hot stand-by redundancy is assumed at both levels. Both Sherbrooke [6] and Cochran and Lewis [7] focus on determining the availability of systems in situations where only a small number of systems is used (<8), which means that the infinite channel queueing assumption (in Palm's Theorem, Palm [9]) does not hold. Cochran and Lewis [7] improve the computational accuracy of determining the probability that the required availability can be met for a small number of systems, given a certain spare parts package. Moreover they present a method to optimise the military aircraft flight programme such that the minimal required availability level is still met given the spare parts package and given that no re-supply is possible during a certain period or only at specific time-intervals. Vujošević et al. [10] consider phased missions with redundancy. Maintenance actions are performed between two successive phases. Unfortunately, this redundancy is also not at system level but at component level.

In this paper, we determine a cost effective spare parts package for a situation where the total amount of available systems is larger than the required number of systems and where only the required number of systems is used (cold stand-by). Furthermore, the total number of systems might very well exceed 8. When we compare our situation with the applications described above, it is clear that:

1. the demand rate for components does not change as long as the required number of systems is available, and
2. determining the probability of availability is more complicated since the number of systems is larger.

To the best of our knowledge, no models exist for cold stand-by redundancy at system level, which means that the systems that are not necessary (all systems above a given amount k) are switched off (stand-by mode) and are only switched on when required. Consequently, components are not subject to failure as long as they stay in the stand-by mode.

Such a situation can occur in military deployment of aircraft and in particular at the Royal Netherlands Air Force (RNLAF). When a squadron of the RNLAF is sent on a deployment, more aircraft are usually taken than strictly necessary in order to guarantee the performance during their deployment. A deployment consists of a number of days during which a certain number of missions has to be flown with a specific number of aircraft. An example is a deployment in which two missions per day have to be flown (one in the morning and one in the afternoon). If the number of aircraft per mission is for example 16 and the number of aircraft available is 20, 4 aircraft are allowed to become unserviceable during the deployment. We are dealing with cold stand-by redundancy of the aircraft. During short deployments (a few weeks) or during the first weeks of a longer deployment no re-supply and no repair of components are performed, so the only spare parts available to replace a failed component within an aircraft are the spare parts in the inventory of the deployment. The question to be answered in this situation is: how many spare parts of each component should be taken on deployment to assure with a certain probability that all missions can be flown with the pre-specified number of aircraft.

The existing METRIC models cannot handle cold stand-by redundancy on system level, which results from the existence of 'spare' aircraft, i.e. the number of aircraft that is allowed to become unserviceable (permitting a certain number of failures). Therefore, using the existing METRIC approach requires either that we consider the parts of the extra aircraft as spare parts inventory, or that we ignore the spare aircraft at all. Both modelling approaches have serious implications in the results. Firstly, if we consider the components of the extra aircraft as spare parts inventory, this would imply that cannibalisation is assumed. However, in a military context, cannibalisation is only done in emergency situations and is certainly not standard policy. Therefore, if cannibalisation is not a common practice the results of the METRIC model might yield a rather low inventory. Secondly, by ignoring the spare aircraft at all, we probably overshoot the inventory because no shortage is allowed.

In order to determine a cost effective spare parts package such that the number of operational systems is sufficient for a specified period in a cold stand-by redundancy situation we extend the METRIC methodology. For this purpose, we develop an exact model and an approximation method. The modelling approach and assumptions made are described in Section 2. In Sections 3 and 4, respectively, the exact and approximation models are presented. We then compared the results of the exact and the approximation method to see how close the results of the approximation method are to the ones obtained via the exact method. Furthermore, we compared the results to a simulation model to check the validity of our modelling approach and assumptions. Both comparisons can be found in Section 5. Finally, we end this paper with some conclusions.

2. Modelling approach

We start with the introduction of some notations. We denote the number of available systems (for instance aircraft) at the beginning of the deployment ($t=0$) as N. The smallest number of systems that is needed to fulfil a mission is denoted by k, where $k<N$ and the other N–k systems are cold stand-by redundant. A deployment consists of a number of missions and it is required that all missions in the deployment can be fulfilled with a probability R^*.

Each system consists of M different components, which can be a rather large number. In case of RNLAF aircraft we assume M to be approximately 1500.

In order to simplify the presentation we consider only one component level, i.e. system is assumed to be single indenture, and we assume the replacement times to be negligible (all replacements can be performed in between two consecutive missions). Every failed component (item) is replaced if a spare part is available. If no spare part is available then the whole system (aircraft in our example) is non-operational for the remaining time. As mentioned before no cannibalisation activities are performed and therefore are not considered in our model.

Similar to the METRIC models, every component i is assumed independent of the other components and failures occur at operational hours (during a mission) according to an exponential distribution with parameter λ_i. Due to this assumption, we are allowed to add the operational hours of the different systems to a total number of operational hours. No distinction needs to be made between which system is active during how many hours because of the "memoryless" property of the exponential distribution. Further, we assume that each replacement of a failed component is carried out immediately (during a mission). This assumption may yield an overestimation of the operational hours per item and consequently to an overestimation of the number of needed spare parts. The impact of this assumption is discussed in Section 5.2.