Int. J. Production Economics 143 (2013) 472–477

Contents lists available at SciVerse ScienceDirect

Int. J. Production Economics

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

# Optimal maintenance and replacement decisions under technological change with consideration of spare parts inventories

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ARTICLE INFO

*Article history:*
Received 14 September 2010
Accepted 4 December 2012
Available online 25 December 2012

*Keywords:*
Technology evolution
Spare parts
Equipment replacement
Maintenance
Markov decision process

ABSTRACT

Classical spare parts inventory models assume that the same vintage of technology will be utilized throughout the planning horizon. However, asset replacement often occurs in the form of a new technology that renders existing spare parts inventories obsolete. This paper aims to study the impact of spare parts inventory on equipment maintenance and replacement decisions under technological change via a Markov decision process formulation. The replacement decision is complex in that one must decide with which technology available on the market to replace the current asset. Under technological change, it is shown that the do nothing and repair options have significantly more value as they allow waiting the appearance of even better technologies in the future.

## 1. Introduction

Maintenance is a key for ensuring the efficient use of equipment as well as an efficient production process. Repetitive breakdowns or operating in bad condition may lead to lower product quality, increased energy consumption and reduced revenue. Therefore, the objective of maintenance is not simply to overcome failures, but also to predict and prevent revenue loss at the management level. Managers must analyze all relevant information to assess the profitability of equipment, give sound investment decisions, and consider possible cost saving. In particular, high spare parts inventory is one important factor in maintenance costs. Asset downtime may increase due to waiting time if necessary spare parts are not available due to poorly managed inventory levels. Hence, the consideration of the spare parts inventory problem is an essential task of managers.

There has been intensive research to study the different aspects of spare parts inventory problems such as management issues, multi-echelon problems, age-based replacement, repairable spare parts, problems involving obsolescence, etc. A review of the spare parts inventory's problems is presented in Kennedy et al. (2002). As the authors comment, spare parts inventories totally differ from other manufacturing inventories. Their function is to assist maintenance staff in keeping equipment in operating condition. The close relation between spare parts inventories and maintenance has been discussed in several articles. Kabir and Al-Olayan (1996) studies the joint-optimization of age-based replacement and spare parts inventory policy (s, S). Under a block replacement strategy, Vaughan (2005) utilizes dynamic programming to solve the spare parts ordering problem while Chelbi and Aït-Kadi (2001) and Saker and Haque (2000) present management policies for a manufacturing system, aiming to optimize jointly the maintenance strategy with continuous review spare items inventory. Chien (2009) and Sheu and Chien (2004) extend the problem by also studying minimal repair for minor failures while De Smidt-Destombes et al. (2006) considers repair capacity of degraded/failed units after they were replaced by spare parts.

However, all of the above models are constructed on the assumption that the same vintage of technology will be utilized throughout the planning horizon. They do not take into account the appearance of new technology with performance improvement. This information is very important for managers who often confront the technology investment decision. They must weigh the benefits of utilizing the available equipment with their stock of spare parts and the revenues of investment in new technology. Nevertheless, there are few articles that take into account technological development in the spare parts inventory problem. They are generally based on the introduction of an economical loss when new technology appears by a cost of obsolescence. Kim et al. (1996) does not explicitly consider an obsolescence cost. They include it in the holding cost in a multi-echelon system. Cobbaert and Oudheusden (1996) develops models that can be seen as extensions of the EOQ formula for fast moving spare parts subject to sudden obsolescence risk. The authors examine the effects of obsolescence on costs under several different conditions: constant obsolescence risk and no shortages are allowed; varying obsolescence risk and no shortages are allowed and finally varying obsolescence risk with shortages. 7 parts inventory and

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http://dx.doi.org/10.1016/j.ijpe.2012.12.003

maintenance strategy by considering a constant rate demand until the obsolescence time.

On the end of the spectrum, models devoted to maintenance optimization involving technological change do not consider the spare part inventory impact (Borgonovo et al., 2000; Clavareau and Labeau, 2009a, 2009b; Dogramaci and Fraiman, 2004; Hopp and Nair, 1994; Karsak and Tolga, 1998; Mercier, 2008). This gap in the literature motivates us to develop an appropriate model to meet management's requirements: optimization of maintenance cost while simultaneously updating information on technological development and considering the impact of spare parts inventory levels to make sound investment decisions. Our main objective is to examine how spare parts inventory levels will influence the replacement decision and also how much better a new technology must be in order to overcome the obsolescence of existing spare parts inventory. In order to focus on this objective, we do not consider spare parts management such as the inventory optimization problem and the potential repair of the spare parts.

We formulate a discrete-time, non-stationary Markov decision process (MDP) to determine the optimal action plan. For modeling technological evolution, we combine the uncertain appearance model (wherein technology change is characterized by the uncertain arrival time of new technology) and the geometric model. The geometric model presented by Bethuyne (2002), Borgonovo et al. (2000), Karsak and Tolga (1998), Torpong and Smith (2003), Natali and Yatsenko (2007, 2008a, 2008b) is a model where geometric functions are utilized to characterize technology change, such as the maintenance/operation cost functions in vintage equipment or in time. Unlike these articles, we present technology change by the improvement of the expected deterioration rate and the expected profit function within a period. We also consider the non-stationary likelihood of new technology's appearance over time. Thereby, we overcome the disadvantages of the geometric model proposed by Borgonovo et al. (2000). Recall Nair (1995), Nair (1997) also consider the non-stationary probability of the appearance of new technologies. However, their model is focused on the problem of capital investment decisions due to technological change rather than physical deterioration of equipment. To simplify its exposition, no salvage values are considered while we establish a reasonable salvage value function which is proportional to the current purchase price of the technology vintage, decreasing in the remaining lifetime and incurs an even greater reduction when it becomes obsolete due to new technology availability.

The remainder of this paper is structured as follows. In Section 2, we present our mathematical formulation model and its assumptions. In Section 3, the performance of our model is discussed through numerical examples. Finally, conclusions and future work are discussed in Section 4.

## 2. Model and assumptions

### 2.1. Problem statement

Consider a single system that includes multiple identical independent components. This system is accompanied by a cargo of $n$ identical spare parts that are utilized for the maintenance of the asset. After these activities, the system will be restored to a better state. We assume that spare parts are not sold separately in the market, i.e., we cannot replenish the spare parts store when it is empty. This is a common assumption for special spare parts because it can be difficult and costly to find original and compatible spare units. In making this assumption we do not consider the optimization of the inventory policy. Our primary goal is to study the impact of the spare parts inventory level on maintenance and replacement decisions under technological change rather than determining what should be the optimal order level/order quantity for the spare parts.

We consider the maintenance of an asset which continuously deteriorates from the as good as new state $x=0$ to the failure state denoted $x=m$. Note that the asset continues to operate in the failed state but unprofitably. Furthermore, degradation is a complex combination of a general wear process of the asset and the ageing process of its components. This complex combination is not explained here or directly modeled in the degradation process. The degradation process is assumed to be characterized by its expected degradation rate per unit of time. Degradation is not obvious and periodic inspections should be performed to determine the true state. The given inter-inspection interval $\tau$ defines the decision epochs.

We assume that only one new technology can appear in a decision interval $\tau$. We introduce $p_{i+1}^{k+1}$ as the non-stationary probability that technology $k+1$ appears in the interval $\tau$ given the latest available technology at decision epoch $i$ is $k$. This probability is non-decreasing in time. The difference in technological generations is modeled by an improvement factor on the expected instantaneous deterioration rate and the accrued profit within a decision period.

Let $(x, k, j, s)$ be the system state of the system at the beginning of the $i$th decision epoch with $s$ spare parts in stock for the maintenance of the asset having deterioration level $x$. The asset in use belongs to technological generation $j$ while the latest available technology in the market is $k$, $k \geq j$. In each decision epoch the possible actions are:

1) Do nothing: The asset continues to deteriorate until the next decision epoch and generates a profit $g_j(x)$. Note that $g_j(x)$ is the expected profit within a period when the deterioration state at the beginning of that period is $x$ and the utilized technology is $j$. The spare parts inventory level is not changed, so the holding cost within this period $i$ is $sc_s$ where $c_s$ is the holding cost per spare part unit in a decision period.
2) Imperfect maintenance restores the asset to a given deterioration level, $\max(0, x-d)$ where $d$ models the maintenance efficiency. An imperfect maintenance cost, $c_1$ is incurred and $\theta$ spare parts are utilized to replace the degraded units, thus the spare part inventory level is reduced by $s-\theta$. As we assume that the maintenance time is negligible, in the next decision interval the asset deteriorates from the level $\max(0, x-d)$ and generates a profit $g(\max(0, x-d))$. Imperfect maintenance can be seen as a partial replacement of deteriorated components.
3) Perfect maintenance restores the asset to the initial deterioration level $x=0$ and the expected profit within next decision interval is $g(0)$. This action requires $\eta(x)$ spare parts that depends on the deterioration state of the asset. A perfect maintenance can be defined as a complete replacement of all the deteriorated items and a cost $c_2$ is incurred $(c_2 > c_1)$.
   Note that as we assume the spare parts are only supplied when we buy a new asset, we can perform maintenance actions if and only if there are sufficient spare parts in stock.
4) Replace the asset by an available technology $h$ in the market $(j \leq h \leq k)$. The replacement time is also considered negligible. A cargo of $n$ spare parts is supplied with the new asset. We assume the spares are only compatible with the same generation asset, hence, after replacement, the spare parts inventory level is $n$ if we decide to replace by a newer generation asset and equals $n+s$ in the case of replacement by same-generation asset. The cost of such a replacement is given by the difference between the purchase price of the new asset $c_{i,h}$ and the salvage value $b_{i,jk}(x)$ of the existing asset. Note that the purchase price of a new technology asset can be