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Joint maintenance and inventory optimization systems: A review

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A B S T R A C T

During the past decades, several joint maintenance and inventory optimization systems have been studied in literature. Compared to the sequential optimization of both models, Kabir and Al-Olayan (1996) reported a remarkable influence on total cost due to their joint optimization method. This review focuses on models that include cost and optimization parameters related to both maintenance and inventory. The purpose of this paper is to review the pertinent literature on joint maintenance and inventory optimization models for non-repairable parts and suggest possible gaps. A classification based on the following seven sets of criteria is made: inventory policies, maintenance characteristics, delays, multi-echelon networks, single-unit versus multi-unit systems, objective function and optimization techniques.

1. Introduction

The main reason a company keeps an inventory of spare parts is to perform maintenance in order to restore the system in such a way that it can perform its intended function. The number of spare parts in inventory is determined by the demand, caused by corrective as well as preventive maintenance, for each spare part. Maintenance relies on the availability of spare parts in order to reduce failure downtime and costs. It is clear that maintenance and inventory management are strongly interconnected and should both be considered simultaneously when optimizing a company's operations. During the past decades, several joint maintenance and inventory optimization systems have been studied in literature. Compared to the sequential optimization of both models, Kabir and Al-Olayan (1996) reported a remarkable improvement on total cost due to their joint optimization method. Several reasons can be found for this cost reduction. On the one hand, maintenance models often rely on the assumption of an inexhaustible number of available spare parts (e.g. Barlow and Hunter, 1960) and on the assumption that these are available without any lead time (Dohi et al., 1998). These assumptions are not always realistic and it would be too expensive for a company to sustain such a system. On the other hand, the unilateral focus on the inventory policy might result in higher costs for maintenance (Acharya et al., 1986). The joint optimization of spare parts and maintenance takes into account the trade-off between maintenance and inventory policies.

This review focuses on papers that include costs (e.g. inventory and maintenance costs) and optimization parameters (e.g. ordering time, replacement time, etc.) related to both maintenance and inventory management. As far as the authors of this paper are aware, this is the first review paper on joint maintenance and inventory optimization taking into account both the costs and parameters related to maintenance and inventory. Another interesting review paper on the joint optimization of maintenance and inventory policies was written by Dohi et al. (1998), but in the end only inventory related costs were included in the models reviewed in their paper. Searching Web of Science and Google Scholar using the keywords 'maintenance', 'inventory', 'replacement' 'joint' and 'ordering' gave us the majority of the papers. The other papers were found by scanning the references and using the 'cited by' option. The scope of our paper is limited to models for non-repairables. If a non-repairable part breaks down, it is removed and replaced by a new part. These non-repairable parts are defined as a 'unit' throughout the entire paper. The reader interested in models for repairable spares is referred to e.g. Park and Park (1986); Chiang and Yuan (2001); Sarkar and Sarkar (2001) and de Smidt-Destombes et al. (2009). The purpose of this paper is to review the pertinent literature on joint maintenance and inventory models for non-repairables and to suggest possible gaps that could lead to interesting future work. A classification based on the following seven sets of criteria was made: inventory policies, maintenance characteristics, delays, multi-echelon networks, single-unit versus multi-unit systems, objective function and optimization techniques. Each of them is discussed in the second section. In the third section, the contribution of the

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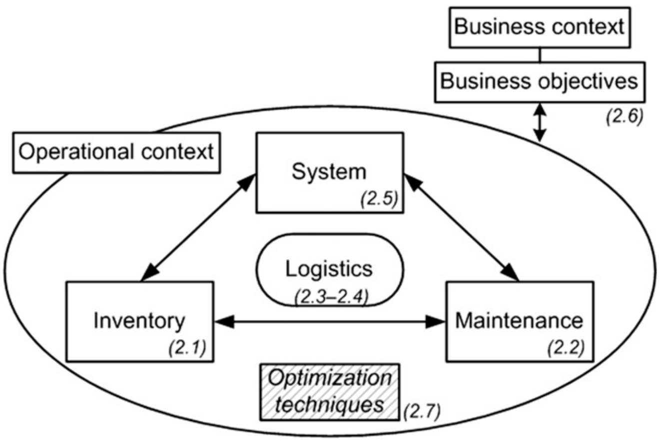

Fig. 1. Framework for joint maintenance and inventory optimization models.

existing papers is described. Finally, some major conclusions and ideas for future research are stated in the fourth section.

2. Characteristics of joint maintenance and inventory optimization models

In order to detect gaps in the existing literature on joint maintenance and inventory models, a framework is constructed first that classifies all characteristics which are of importance when considering these models. The framework is depicted in Fig. 1. All characteristics of Fig. 1 are discussed in more detail in the specific sections shown in Fig. 1. The literature discussed in Section 3 of this paper is classified according to the defined characteristics in the framework. Based on this classification it is possible to determine which research has been done and still has to be done on joint maintenance and inventory models.

2.1. Inventory characteristics

Inventory can be reviewed continuously or periodically and both approaches have been used in joint systems (see Table 1, column I). In the continuous review policy, the inventory levels are checked continuously and when a certain condition is met (e.g. the amount of spare parts drops below a certain level), spares are ordered. Two well-known and often used continuous review policies are the (s,S) and the (s,Q) policy. Using an (s,S) policy, one orders spares to reach the order-up-to level (S), whenever the inventory level drops below s. When Q units are ordered each time inventory drops below s, it is called an (s,Q) policy. When there is a per unit demand, both systems give the same result if Q equals S minus s. A special case of a continuous (s,Q) review policy, which is mainly used for low cost and high demand spare parts, is a two-bin policy where a replenishment order is placed when the first bin is empty. At that time, one starts to use the second bin and a new bin is ordered.

In a periodic review policy, at the beginning of each cycle, spares are ordered depending on e.g. the forecasted demand of the next period. As an example, let R be the length of the review interval. Using the (R,S) policy, one orders up to S units each time at the beginning of the review interval.

Another important inventory characteristic to take into account is the consideration of a single-unit or multi-unit inventory. When failure frequencies are high or lead times are very long, it might be interesting to keep more than one part in stock, even though a single unit system is under consideration. On the other hand, keeping multiple units in inventory increases the risk of obsolescence. Obsolescence is a major (cost) issue for spare parts which are rarely needed for replacement (Kennedy et al., 2002).

2.2. Maintenance characteristics

2.2.1. The degrees of maintenance

Different degrees of maintenance are discussed in the literature (Wang and Pham, 1996). When the fixed system is as good as new after the maintenance actions, it is called a *perfect repair.* Unfortunately, most repairs do not fix the system perfectly. A *minimal repair* restores the system to an as bad as old state, which means that the system has the same failure rate after repair as it had just before the repair. *Imperfect repair* restores the system to a state somewhere in between as good as new and as bad as old. A less favorable degree of repair is *worse repair* in which the systems condition is worse than just before failure. In some circumstances one might even have a *worst repair*, which means that the system breaks down completely after maintenance.

The reason to consider the degrees of maintenance even for non-repairable parts, as considered in this paper, is that a replacement of a part by a new part can be imperfect too. Wrong installation of the part, outlining errors etc. can result in imperfect replacement. Moreover, when considering multi-unit systems, the replacement of one broken unit does not always make the entire system perfect again. A simple example is a bicycle wheel, where the entire wheel is seen as a system that consists of multiple non-repairable units, the spokes. When one spoke breaks, the replacement of it does not result in an as good as new system or wheel; it results in an imperfect repair of the system. Armstrong and Atkins (1998) make a distinction between a major and a minor failure and Nguyen and Bagajewicz (2009) assume imperfect preventive maintenance. All other papers considered in this review assume that the systems are perfectly maintained or do not mention any assumption concerning the degree of restoration.

2.2.2. Maintenance strategies

Three major maintenance strategies can be distinguished. The most reactive strategy is failure based maintenance (FBM) (also called corrective maintenance). Whenever a failure occurs, the units are replaced or repaired as soon as possible. If no spare part is available, the maintenance is delayed and possibly high downtimes are induced.

A second well known strategy is preventive maintenance. Several policies might be classified as being preventive. A review is provided by Wang (2002) and a brief explanation of the most important preventive maintenance policies for non-repairables, considering both single-unit and multi-unit systems, is provided. For single-unit system these policies are

- Age-based preventive maintenance: a unit is always replaced at its age T or failure, whichever occurs first, where T is a constant (Barlow and Hunter, 1960).
- Block-based or periodic preventive maintenance: a unit is replaced at prearranged times kT $(k=1, 2,\ldots,n)$ independent of the failure history of the system.
- Sequential preventive maintenance: when machines and their parts become older, they need more frequent maintenance. To take this into account, time intervals become shorter as time passes by.
- Failure limit maintenance: units are replaced as soon as the failure rate or other reliability indices of a unit reach a predetermined level. All failures occurring in the meantime are corrected by replacements.