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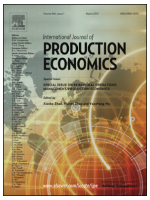

Optimal prognostic distance to minimize total maintenance cost: The case of the airline industry

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ABSTRACT

Prognostic distance is the time interval needed to gather information to predict a future failure and to take appropriate action. Within the calculated prognostic distance, there is an increased accuracy of a system's failure prediction. In such situations, finding an optimal prognostic distance is important to decrease total cost related to the maintenance function. Therefore, this paper considers the problem of finding an optimal length of the prognostic distance to be used in the prognostic health management (PHM) system to minimize the total maintenance cost. By characterizing the relationships of various cost components to the length of the prognostic distance, a general expression for the total maintenance cost is developed as a function of the prognostic distance and the generic constraints are identified. In view of the difficulty to develop an exact form of the mathematical functions and/or a closed form solution for the formulated optimization problem, a practical procedure to find an optimal or near-optimal prognostic distance is then described and illustrated with a case study from the airline industry. The proposed model and practical procedure use all gathered operational and cost parameters from the historical data to determine a near optimal prognostic distance through simulation or an appropriate optimization technique. Our proposed approach leads to a better interpretation of PHM results and thus helps translate PHM information to maintenance actions and policies which can assist in minimizing life cycle costs and maximizing the availability across an airline network.

1. Introduction

Many firms facing stiff competition need to reduce their equipment maintenance cost as much as possible while providing excellent service without disruptions. For example, with the increasing cost of fuel and security procedures, airline industry is struggling to provide adequate service at reasonable prices. Any reduction in maintenance cost in the airline industry, therefore, enhances the competitiveness of an airline. Traditionally, maintenance diagnostics and repair procedures have been used to ensure higher level of equipment availability at reduced cost. However, recent research has shown that prognostics where an attempt is made to proactively predict and diagnose a possible failure in the future is relatively more effective in decreasing maintenance cost. Therefore, *prognostic health management* (PHM) is now considered to be a preferred approach to enhance equipment availability by decreasing downtime for repair at a reduced cost. With the help of better prognosis, the component useful life time is maximal making it possible to adjust the failure rate downwards and to significantly extend the component's service life time (Fritzsche, 2012).

Application of PHM requires the ability to forecast a possible failure in the future and the actions that can be taken to ensure that equipment maintenance and repairs are undertaken prior to the time at which a future failure is expected. The time interval of an organization's ability to gather information needed to predict a failure and to forecast a future failure for taking appropriate action is called *prognostic distance* (*PD*), according to Sandborn and Wilkinson (2007). A significant improvement in the forecast quality of maintenance optimization algorithms is achieved within the prognostic distance. This allows a possible backward shift of the latest possible instance of time for spare parts delivery. It increases the probability that the required spare parts are available at the right time and at the right place. It also avoids the delivery of spare parts to wrong destinations because of a too early delivery and a premature unscheduled failure. Selection of an appropriate prognostic horizon, therefore, will avoid unnecessary transshipments and hence the decrease in transport cost. A faster exchange of components can be guaranteed, resulting in shorter downtimes and thus decreasing the downtime cost. As a result, the role of

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prognostic distance in decreasing the total maintenance cost has been a topic of recent research in PHM (Sandborn and Wilkinson, 2007; Feldman and Sandborn, 2008).

Use of *prognostic distance* (PD) can decrease the total cost by transferring the need for unscheduled maintenance into scheduled maintenance within a finite prognostic horizon. Increased scheduled maintenance will result in longer maintenance free intervals and thus decrease maintenance cost over time. However, if PD is too long, the forecast reliability may be quite low. On the other hand, if PD is too short, the cost of repair may be too high. Therefore, it is necessary to find an appropriate length of prognostic distance to minimize the total maintenance cost and to provide reliable and safe use of the equipment without interruptions or delays. While several authors including Sandborn and Wilkinson (2007), Saxena et al. (2008), Feldman and Sandborn (2008), and Gould (2011) identified the prognostic distance (PD) as a new metric for measuring PHM effects, they did not consider the integration of the prognostic distance in existing PHM models or how this integration could be realized. An optimal prognostic distance can provide additional time to order spare parts ahead of failures (Jazouli and Sandborn, 2010). However, current research does not provide any procedure for finding an optimal (desired) length of prognostic distance to use.

In this paper, we propose a general mathematical model for minimizing the total maintenance cost of equipment considering the appropriate choice of the prognostic distance. Additionally, we provide a method (applicable to most of the underlying planning problems, but especially in the aviation industry) for an a priori adaptation/definition of an optimal (cost vs. revenue) prognostic distance. With this procedure, improved predictability of the planned replacement of exchanges occurs within this prognostic distance, i.e., unscheduled maintenance is transferred to scheduled maintenance because of higher costs for unscheduled events (Sandborn and Wilkinson, 2007). However, our proposed general model does not specify the exact form of the mathematical functions as they are very much situation dependent. For each specific practical problem, the mathematical functions may either be continuous and differentiable or such that only some numerical optimization techniques can be used to solve the problem. We illustrate this through a case study in the airline industry.

The rest of this paper is organized as follows: Section 2 briefly reviews the literature related to the PHM research and the performance metrics used. Our generic mathematical model to find the optimal prognostic distance to minimize the total maintenance cost is presented in Section 3 where the limitations and practical means of testing the proposed model are also described. Use of prognostic distance in PHM to minimize total maintenance cost is illustrated through a case study in the airline industry in Section 4. Finally, Section 5 concludes the paper with a summary of our findings and some fruitful directions for future research.

2. Literature review

Maintenance strategies can be divided into two broad categories: Performance-Based Logistics and Condition-Based Maintenance. Performance-Based Logistics is primarily used for weapons system support, and is not further investigated in this paper. Nicolai and Dekker (2006) categorized the Condition-Based Maintenance strategies for PHM in corrective and preventive maintenance over a finite (dynamic) and an infinite (stationary) prognostic horizon. The finite models are dynamic, since these models can generate dynamic decisions that may change over the planning horizon. Due to the complexity of PHM technology, it is very important to identify the value of the spare parts in order to generate the greatest benefits of investments for a potentially large number of system components within the limited resources. This means that the most relevant challenge is to set an appropriate metric for measuring the effects of PHM on operational and support performance (Luna et al., 2009).

Considering the importance of performance metrics and the role of prognostic distance in the design and operation of prognostic health management (PHM) systems, this section is organized and limited to a brief literature review related to these two concepts.

2.1. Maintenance performance metrics

Table 1 lists various performance metrics used in maintenance optimization models, indicated by a representative of the published articles. The first four metrics, maintenance cost, maintenance quality, overall equipment effectiveness and number of maintenance intervention, are not always explicitly mentioned by the authors as an optimization criterion. However, these four metrics are most widely used as primary or secondary maintenance optimization criteria.

Quan et al. (2007), Certa et al. (2011) and Flage et al. (2012) explicitly mention the minimization of maintenance cost as an optimization value. Other objectives such as personnel management (Martorell et al., 2005; Quan et al., 2007; Flage et al., 2012), inventory of spare parts (Certa et al., 2011) and capital replacement decisions (Liu et al., 2005) are also considered in the literature. Availability as a maintenance optimization criterion was first introduced by Dekker (1996) and then studied by Martorell et al. (2005) and Certa et al. (2011). Scarf (1997), Martorell et al. (2005), Bucher and Frangopol (2006), Certa et al. (2011) and Flage et al. (2012) optimized reliability while Martorell et al. (2005) and Certa et al. (2011) optimized maintainability. Other performance metrics such as environmental impact (Al-Najjar, 2007), safety or risk (Martorell et al., 2005; Liu et al., 2005; Flage et al., 2012), output quality (Van Horenbeek et al., 2010), output quantity (Al-Najjar, 2007; Van Horenbeek et al., 2010), lead time (Quan et al., 2007; Al-Najjar, 2007; Certa et al., 2011), society acceptance (Al-Najjar, 2007) and value of maintenance (Marais and Saleh, 2009) have also been discussed in the literature.

2.2. PHM and prognostic distance

To achieve system reliability, availability, supportability, and maintainability we introduce prognostic health management (PHM) as a key enabler. PHM is utilized to analyze system performance and environmental data. Various methods or algorithms are used to determine the degradation of a component or system (Sun et al., 2012). The output from a PHM system is the calculated prognostic distance of a component, which provides the decision maker of a company with lead-time to perform maintenance actions. The goal is to perform all maintenance actions until the failures occurs. Under a PHM system with a calculated prognostic distance, planners or decision makers operate proactively to reduce life-cycle cost (Haddad et al., 2012).

2.2.1. Prognostic health management

Prognostic health management is an often and broadly defined term for planners and designers to find ways to increase system availability, improve system reliability, and reduce the cost of system operations (Luna et al., 2009). The objectives of PHM are to reduce logistics footprint, logistics response time for spare parts, life-cycle cost, and increase availability and reliability for all components (Wheeler et al., 2010). PHM combines sensing, recording, and interpretation of operational parameters to monitor and improve a system's health.