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Integrated scheduling of preventive maintenance and renewal projects for multi-unit systems with grouping and balancing

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ABSTRACT

This paper studies preventive maintenance and renewal scheduling for multi-unit systems. We develop an integrated optimization method to schedule preventive maintenance and renewal projects by grouping them and simultaneously finding the optimal balance between them. Grouping and balancing are resource utilization techniques to reduce the costs of maintenance without reducing the level of maintenance. We next model the problem as a pure integer linear programming formulation to minimize the costs of maintenance and renewal projects and their relevant preparatory works and downtime costs over the planning horizon. We use a numerical experiment with sensitivity analysis to illustrate the model, and the potential cost reductions that using such an integrated model may lead to. Applications of this model arise in the maintenance of railways, roadways, electricity distribution networks, and distributed pipeline assets. Due to the complexity of the model, two heuristic algorithms based on decomposition approach with problem-specific cutting planes are applied to tackle the problem. Experimental results show that our integrated optimization approach performs well in reducing the cost of preparatory works through proper scheduling. Finally, a case study for the maintenance of railway track shows that using our integrated approach reduces the maintenance and renewal costs by up to 14% as compared with the spreadsheet based approach used currently at the operation.

1. Introduction

Maintenance is the work performed to keep a system in an appropriate condition and working order. It plays an important role in industries in which the loss resulting from a system failure is significant. Maintenance activities can be divided into preventive, corrective, and predictive maintenance (Moubray, 1997; Murthy, Atrens, & Eccleston, 2002). Preventive maintenance (PM) involves a set of activities such as testing, measurement, and adjustment carried out to prevent unexpected system breakdowns. PM is often performed routinely based on time or cycles. Corrective maintenance (CM) is an unscheduled maintenance or repair performed after failures of the system have occurred and to restore the system to an operational state. CM could be either planned (run-to-failure) or unplanned. Predictive maintenance involves the use of modern measurement and signal processing methods to accurately predict and diagnose equipment condition during operation (Moubray, 1997; Murthy et al., 2002). An effective preventive maintenance program can reduce the probability of costly corrective replacement and repair, as well as avoid excessive maintenance, thus significantly cutting down servicing costs (Yang, Ma, & Zhao, 2017).

The focus of the present paper is on scheduling preventive maintenance and preventive renewal activities. One of the main advantages of PM is that it can be planned ahead and performed at a convenient time. Often preparatory work such as shutting down a unit or transportation of the maintenance crew and machinery has to take place before maintenance can be performed (Chalabi, Dahane, Beldjilali, & Neki, 2016). PM activities are costly when frequently performed since they increase the downtime of systems. It is desirable to reduce the costs of maintenance without reducing the level of maintenance (Budai, Huisman, & Dekker, 2006).

One technique to reduce PM costs is to group the executions of maintenance and renewal projects (repair and replacement in the CM context, e.g. Dekker, Wildeman, & Van der Duyn Schouten, 1997; Moghaddam & Usher, 2011a). Grouping allows savings on the preparatory work costs. However, it often implies that one deviates from previously planned execution times, possibly increasing costs due to performing a maintenance activity earlier than necessary (Budai, Dekker, & Nicolai, 2008). Another technique to reduce PM costs is to balance maintenance and renewal and determine the economic life of a system component. In general, a

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system component deteriorates with age, and the need for maintenance increases during the final periods of its technical life (Andrews, 2012). Accordingly, it can be economical to renew the component earlier than its physical life to prevent successive costly maintenance activities, or to be able to combine its renewal with other renewal projects. In this paper, finding a balance between maintenance and renewal is called "balancing".

This paper presents an optimization model that integrates grouping and balancing for planning preventive maintenance and renewal projects of multi-component assets which are spread out geographically. These assets are called multi-unit systems. A multi-unit system includes several multi-component systems in sequence. In Fig. 1 below, we show the structure of a typical multi-unit system, consisting of K units in which each unit may consist of I components. In a multi-unit system, each unit may have special maintenance requirements because of differentiation in factors such as the importance of the unit, its environment, and the component characteristics. The downtime cost of a multi-unit system is high, as the whole system will be out of service if a component in one unit is unavailable.

Our optimization model minimizes the costs of maintenance and renewal projects and their relevant preparatory works over a discrete number of time periods. In each period, it is assumed that one of the following three distinct actions can be performed for each component of the units (Moghaddam & Usher, 2011a):

(a) Do nothing: In this case, no action is to be performed on the component. This is often addressed to as leaving a component in a state of 'bad-as-old', where the component continues to age normally.
(b) Do maintenance: In this case, the component is maintained, which places it into a state somewhere between 'good-as-new' and 'bad-as-old'.
(c) Do renewal: In this case, the component is removed from the unit and replaced by the new one, immediately placing it in a state of 'good-as-new', i.e. its age is effectively returned to time zero.

The preventive maintenance and renewal scheduling problem (PMRSP) can be defined as designing the best sequence of actions (a), (b) or (c) for each component of the units over a planning horizon such that the total costs are minimized. The applications of our model are at a strategic level with time horizons of one to several years or at a tactical level covering a medium-long time horizon (weeks to a year). Although our optimization model is formulated for multi-unit systems, it can be easily adapted to any types of systems or even a single-unit system by assuming $K = 1$.

The maintenance of a railway, roadway or electricity network are the typical application areas of a multi-unit system. Large

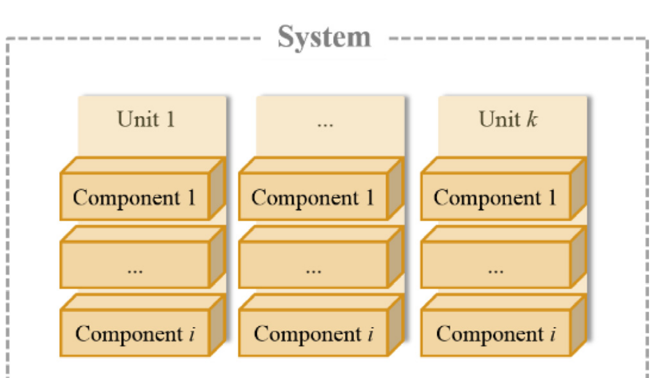

Fig. 1. The structure of a typical multi-unit system with several components.

benefits can be realized if preventive maintenance and renewal scheduling of these infrastructure assets can be improved (Lidén & Joborn, 2017). As an example of monetary volumes, the European countries are reported to allocate 15–25 billion EUR annually on maintenance and renewals for a railway system consisting of about 300,000 km of track giving an average of 70,000 EUR per km track and year (see EIM-EFRTC-CER Working Group, 2012). Therefore, a saving of millions of Euros may be obtained through small improvements in managing track maintenance and renewal (Acharya, Mishalani, Martland, & Eshelby, 1991). In Section 5.5, we perform a case study in the railway sector.

According to the best of our knowledge, this study is the first work which integrates the grouping and balancing techniques for preventive maintenance and renewal scheduling of multi-unit systems. This paper presents a new hierarchical structure for setup costs which considers economic dependency between components of multi-unit systems. The developed setup configuration shows the potential benefits of grouping maintenance and renewal projects. In this paper, the economic life of the system components is determined by finding the optimal balance between maintenance and renewal while considering their effect on each other. These ideas are formulated in an integer optimization model which jointly schedule preventive maintenance and renewal projects.

This paper includes two illustrative examples and a real-world case study to show the potential cost reductions that using our integrated model may result in. Example 1 (see Section 3.1) illustrates the benefits of grouping maintenance and renewal activities in multi-unit systems. Example 2 (see Section 4.3) visually demonstrates the impact of the model parameters such as the length of planning horizon and the system downtime cost on the structure of optimal preventive maintenance and renewal schedules.

The rest of this paper is organized as follows. We review the related literature to the PMRSP in Section 2. In Section 3 the implications and importance of grouping and balancing are discussed and the model assumptions are presented. In Section 4, the mathematical model is investigated in detail. Numerical experiments with sensitivity analysis are carried out to gain more insight into the integrated model. Section 5 proposes heuristic algorithms to solve the problem and discusses the results of computational tests. The benefits of our integrated approach in cost savings are also reported. A real-world application of the proposed model and algorithms is presented. Finally, Section 6 concludes the research with summary and remarks.

2. Literature review

Maintenance optimization models have been widely developed and used to optimize maintenance schedules for a variety of systems. Due to the complexity of analyzing systems with multiple units, most maintenance optimization studies consider a single-unit system with one or several components (Ko & Byon, 2017). The focus of the present research is on multi-unit systems with economically dependent components that provide the opportunity to group preventive maintenance and preventive renewal projects. The existing literature in this field is extensive, and it is beyond the scope of this article to discuss all the relevant research contributions. Instead, we refer the reader to related surveys for a comprehensive review of previous work by Cho and Parlar (1991), Dekker et al. (1997), Wang (2002), Nicolai and Dekker (2008), and Van Horenbeek, Pintelon, and Muchiri (2010). Detailed description of maintenance policies such as failure-based maintenance and condition-based maintenance with different types of dependencies between the components are out of scope of this paper, as well as modeling component failure processes caused by internal-based deterioration and external environmental shocks. In the following,