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The scheduling of maintenance. A resource-constraints mixed integer linear programming model ☆

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ABSTRACT

The scheduling of preventive maintenance is crucial in reliability and maintenance engineering. Hundreds of parts compose complex machines that require replacement and/or repairing. Maintenance involves the machine vendor (1), the machine user (2) and the service maintenance provider (3). The vendor and the maintenance service provider have to guarantee a high level of availability and productivity of the machines and maintain their down-time at a minimum even though they are installed worldwide and usually far from the vendor's headquarters and/or the locations of the provider's regional service offices. Moreover, many companies have great profits from maintenance and spare parts management.

This study aims to illustrate an original mixed integer linear programming (MILP) model for the cost-based, reliability-based and resource-constraints scheduling of preventive maintenance actions. The model minimizes the total cost function made of spare parts contributions, the cost of the execution of the preventive actions and the cost of the additional repair activity in case of unplanned failure. The cost of the personnel of the producer and/or the maintenance service provider is also included. Finally, the paper presents a case study in a what-if environment demonstrating the effectiveness and the novelty of this study in real and complex applications.

1. Introduction

Literature classifies maintenance planning and scheduling into two major categories: the scheduled maintenance (1) and the unscheduled maintenance (2). The second deals with emergency breakdowns. The first includes preventive and routine maintenance (1.1), and the scheduled overhauls and corrective maintenance (1.2). The unscheduled maintenance is stochastic in nature. According to Duffuaa and Al-Sultan (1999) "this stochastic nature makes maintenance scheduling a challenging problem".

Many companies produce and distribute worldwide complex production systems and machines. They also offer several maintenance services that include spare parts management, preventive maintenance actions, corrective maintenance actions, warranty management, and training of personnel. Maintenance service is a strategic activity to have a high level of productivity, quality, safety, and reliability of production systems. Furthermore, this can be a very expensive and labor-intensive service but also an opportunity for economic returns by post-sale services. The cost of maintenance can be also significantly affected by logistics decisions, including the number and location of service providers and regional offices, the inventory management of spare parts, and the organization of maintenance crews.

This paper illustrates an original cost-based, reliability-based and capacity-constraints optimization model for the scheduling of the maintenance and repair tasks within a maintenance plan (i.e., task plan).

The maintenance tasks refer to the set of activities necessary to replace a component or a group of components subjected to wear and tear within a generic plant or machine. The group of maintenance tasks including all the repairing and/or replacing activities that a generic machine or a plant require over its own life-cycle is named task plan. Each task to be scheduled usually involve spare parts, personnel (e.g., local personnel or service providers' operators), resources and equipment. The frequency of each task is generally determined by the failure rates (i.e., the curve of failure probability to the machine up time) of the most critical component of the task. The general rule complied by the maintenance service provider in presence of complex components is assuming a constant failure rate (i.e., Assumption 1) corresponding to the average

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value suggested by the machine vendor. This assumption is critical in the presence of mechanical and mechatronic components that are mostly diffused in the modern automatic machines. However, Assumption 1 is often necessary due to the large amount of parts and components involved simultaneously and physically connected. Another assumption that frequently follows the constant failure rate is the constant frequency to execute preventive maintenance tasks (i.e., Assumption 2).

Furthermore, the provider commonly executes the preventive task on a component after a time equal to the mean time to failure (MTTF) of the task/component from the previous action and/or replacement (Assumption 3).

Unfortunately, when applied to real instances, these assumptions are not consistent, especially in presence of parts subject to "aging", e.g., "early wear out" components or "old age and rapid wear out" components (Manzini, Regattieri, Pham, & Ferrari, 2010). Furthermore, the parts and components of a production system, e.g., a packaging machine, are not "as good as new" items after repairing or a preventive action, even in case of the part replacement.

To find more concrete and realistic solutions and go beyond to the illustrated assumptions, this paper presents an original mixed integer linear programming (MILP) model for the determination of the maintenance schedule that minimizes the total cost associated to the task plan. These costs include the preventive maintenance contributions, the corrective contributions (the so-called unplanned costs), the spare parts management, and the labor accounted by the maintenance operators.

The task plan scheduling is the result of the assignment and sequencing of different preventive maintenance tasks to a set of available service orders. This set is usually known in advance and results from a deal between the supplier of maintenance service, i.e., the previously defined "service provider", and the client which requires for the maintenance of its plant. The generic service order corresponds to a time bucket located on a specific calendar date. This is the reason we adopt the terms time bucket to indicate a service order of a finite capacity.

The client purchases a calendar of preventive maintenance time buckets, and the service provider has to assign maintenance tasks to these buckets, controlling the availability of the system and reducing costs to realize a profitable service. In other words, the aim of the provider is to minimize the total cost of maintenance while guaranteeing a standard level of availability (i.e., up time) of the production system.

The remainder of this paper is organized as follows. Section 2 presents a literature review on the scheduling of the preventive maintenance. Section 3 illustrates the proposed maintenance planning model. Section 4 presents a significant case study which inspired the development of the proposed model. A sensitivity analysis is conducted to demonstrate the effectiveness of the proposed planning model. Finally, Section 5 discusses the conclusions and further research.

2. Literature review

The literature presents many contributions to preventive maintenance and scheduling issues for production systems with a special focus on operations. In particular, management science and operational research frequently discuss scheduling and optimization problems, but few studies deal with reliability and maintenance engineering (Manzini et al., 2010; Regattieri, Manzini, & Battini, 2010).

Sherwin (2000) presents a review and a discussion of the main issues in maintenance management. He also attributes significant and strategic importance to data collection to conduct effective planning and scheduling of maintenance tasks.

Many studies deal with maintenance planning applied to production and operations, e.g., models and methods to schedule preventive maintenance activities on manufacturing systems subject to failure, i.e., corrective maintenance (Hadidi, Al-Turki, & Rahim, 2012; Xiang, Cassady, Jin, & Zhang, 2014). In particular, they formulate integrated planning models to simultaneously face production and maintenance planning (Cassady & Kutanoglu, 2005; Kuo & Chang, 2007). These contributions are not based on the reliability of parts and components involved and are not suitable to strategically design a task plan tailored to a selected production system subject to failure. They do not involve the management of spare parts and the assignment of tasks in agreement with finite capacity constraints.

Duffuaa and Al-Sultan (1999) present one of the first mathematical formulation of the stochastic programming for scheduling maintenance personnel. It incorporates deterministic and stochastic contributions. Heuristic algorithms to solve the maintenance scheduling problem are proposed by Raza and Al-Turki (2007). This adoption of heuristic and meta-heuristic approaches is supported by a demonstration of the NP-hard problem complexity.

Several contributions present interval time models, i.e., reliability based static state models for the determination of the time to replace components without any discussion on capacity and time constraints, which are very important in real applications (Hui, Zheng, Liu, Zhao, & Sun, 2013). Simple and basic models are collected and illustrated by Jardine and Tsang (2006). More complex and recent contributions based on MILP are illustrated by Perez Canto (2011) and Bell and Percy (2012).

Kim and Yoo (2012) discuss the planning of maintenance actions combined with manpower by the determination of the workforce size as a relevant issue in the presence of labor-intensive actions and high labor costs.

Alardhi and Labib (2008) present a preventive maintenance scheduling model based on mixed integer programming, which is the modeling approach adopted by the authors of this paper. They include crew constraints, maintenance window constraints and time-limitation constraints, but they do not include reliability based functions.

Tam, Chan, and Price (2006) present three integer linear programming models for maintenance interval determination, minimizing cost and maximizing system availability. They adopt a Weibull distribution for failure rates, but they do not consider time capacity constraints for the execution of a task. Personnel assignment and costs are not included. Finally, spare parts contributions are not modeled.

Moghaddam and Usher (2011) present two non-linear models. The first minimizes the global cost; the other maximizes the system reliability. They adopt increasing failure rates, but they do not consider the time capacity constraints and the time duration of tasks.

Ebrahimipour, Najjarbashi, and Sheikhalishahi (2013) present non-linear models for parallel machines focusing on the difference between maintenance (not as good as new) and replacement (as good as new) activities. They use a Weibull distribution of failure rates, and tasks take a uniformly distributed amount of time. These models are not suitable to scheduling multiple tasks for a complex machine in agreement with the time capacity constraints.

Different modeling approaches to preventive maintenance scheduling are illustrated by Zhang and Nakamura (2005) and Xu, Xueshan, Wang, and Sun (2012), the first illustrating a simulation model and the latter heuristic algorithms, which do not support the decision making techniques adopted by the authors of this paper.