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On the combined maintenance and routing optimization problem

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ABSTRACT

This work focuses on the problem of planning and scheduling maintenance operations for a set of geographically distributed machines, subject to non-deterministic failures with a set of technicians that perform preventive maintenance and repair operations on the machines at the customer sites within a specific time window. This study presents a two-step iterative approach. In the first step, a maintenance model determines the optimal time until the next preventive maintenance operation, its frequency, and the time window for each customer, while minimizing the total expected maintenance costs. In the second step, a routing model assigns and schedules maintenance operations to each technician over the planning horizon within the workday. This two-step iterative process balances the maintenance cost, the failure probabilities, and waiting times at each customer. The novelty of this work lies in the integration of maintenance scheduling and a routing model that considers several machines.

1. Introduction

It is well known that thoughtful planning and scheduling of maintenance operations leads to significant improvements in the reliability of an industrial installation or a distribution network [16]. Maintenance planning determines the set of operations, time intervals, and resources (staff, supplies, and spare parts) necessary to conduct maintenance operations [6]. Companies often delegate maintenance planning to staff with experience, trusting in their intuition and knowledge. When they are faced with scheduling maintenance operations manually, even the most experienced planners can only consider a limited number of possibilities. Moreover, it is often the case that to manually generate a feasible schedule, they need to invest a significant amount of time.

When the machines are geographically distributed, the problem becomes even more complex because in addition to allocating maintenance operations to the workforce (e.g., crews) it is necessary to sequence their visits. The combinatorial optimization problem of finding the best set of routes (sequence of visits) for a workforce crew is known as the *vehicle routing problem* [21]. In a broad sense, this problem determines the best set of routes to be performed by a set of vehicles (crews) in order to serve a set of geographically-spread customers (machines) subject to some operational constraints. Among several variants of this problem, the vehicle routing problem with time windows (VRPTW) is closely related to planning and scheduling maintenance operations. In the VRPTW, the crews have a limited capacity (e.g., workday) to serve customers for whom maintenance operations must be started within given time windows.

Several applications for the combined maintenance and routing problem arise naturally in the oil and gas industry, telecoms, public utilities, health care, and the financial sector. For example, daily operations in an upstream oil and gas company involve managing a network of interconnected pumping stations. Because of the prohibitive costs of stopping the operation, the company incurs in an overly expensive maintenance policy that ensures the highest service levels at the intermediate stations. However, this policy translates into excessive technician visits to the stations, spread throughout a vast region. This type of company would be interested in other options that explore the tradeoff between service level and operational costs. Another application arises in maintenance operations of security hardware (e.g., video cameras) in a network of automatic teller machines (ATM). Most banks outsource these maintenance operations to a third party, who commits to perform periodical preventive maintenance within certain time windows. Upon occurrence of failures or accidents (e.g., vandalism), the technicians must go to the ATMs on a tighter

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time frame. The objective consists of reducing the operational costs, while maintaining a service level stipulated in the contract.

In this paper we consider a set of machines that are geographically distributed over a region. These machines are subject to unforeseen failures that result in downtime and hence loss of productivity. To reduce the occurrence of these unforeseen downtimes, a Preventive Maintenance (PM) operation is scheduled with a certain frequency. A set of technicians who are missioned to visit these machines to perform PM operations is also considered. When a machine fails suddenly, the maintenance crew has to perform a *repair* operation, called Corrective Maintenance (CM). Each machine starts in *as good as new* condition and after the repair or PM procedure the machine is assumed to be in as good as new condition again. Both operations, CM and PM, are assumed to take a certain but distinct amount of time to be performed, where the CM duration is higher than PM duration. Each PM operation is associated with a hard time-window dependent of the total expected cost, i.e., the time-window is calculated using a fixed amount of cost in which the optimal maintenance cost may increase to provide a flexibility for PM operation´s date. The purpose of the time-window is to generate a time interval within which a PM operation can occur, and in which the technician can start the PM operation. A technician must arrive before the upper limit of the time window. If the technician arrives before the lower limit of its time window, he or she must wait to start the PM operation at the beginning of the time window. Given a planning horizon, this problem consists of determining a joint best routing-maintenance policy for all technicians and machines. The problem aims to minimize the total expected maintenance cost (CM and PM costs as well as the cost of unavailability). The novelty of our approach lies in combining maintenance and routing models that determine when and how many PM operations are to be performed on the whole group of machines, and determine, for each technician the operations to perform and the sequence in which these PM operations must be carried out.

To solve this problem we propose a solution approach which integrates these two models iteratively, called the Combined Maintenance and Routing Model (CMR). Firstly, with the assumption of zero waiting times, the maintenance policy is optimized in order to determine the optimal time when each PM operation should be executed along with its corresponding time window, minimizing the total expected maintenance costs. Secondly, using the output from the maintenance model, the routing model is solved in order to determine the PM operations to be performed by each technician and the start time of service at each customer (or machine). After this, the expected waiting time is calculated for each customer and the maintenance model is solved again with new information as input in order to determine when each PM operation should be executed. The process continues until there is no improvement in the objective function for a fixed number of iterations or the iterative process reaches the maximum allowed run time.

The remainder of this paper is organized as follows. Section 2 reviews the literature related to maintenance and routing problems. Section 3 introduces the notation and the problem definition. Section 4 presents the maintenance model. Section 5 is dedicated to the mathematical formulation of the routing problem. Section 6 states the connection between the maintenance model and the routing model. Section 7 shows the benchmark procedure, a simple procedure to generate a feasible maintenance schedule in order to test the relevance of integrating the routing model within the maintenance policies. Section 8 provides some numerical experiments on random test instances where our CMR approach is compared to the benchmark procedure. Section 9 illustrates the performance of our proposed approach in an example inspired by a real-world case in the Oil and Gas industry. Finally, Section 10 concludes this work and provides possible research directions.

2. Literature review

A maintenance policy is the combination of inspections (for monitoring purposes), preventive and corrective operations intended to restore a machine to a state in which it can perform its required functions. Lugtigheid et al. [12], Crespo [4] and Wang and Pham [22] describe the inputs of a maintenance policy model as the failure model. Based on the available information, the failure model determines the probability that a machine fails during a certain period of time, the maintenance operation characterization which can be either preventive or corrective or both, and the line of maintenance which consists of the location and maintenance support, i.e., the place where the maintenance is performed and the resources used. The time to failure (lifetime) is one of the most important features of a maintenance model characterized mainly by its cumulative distribution function and is used in *replacement and inspection models*.

In the literature there are different applications of replacement and inspection models. Classic replacement models for mono-component machines assume that a machine is always replaced completely, the replacement is done instantaneously, i.e. consumes no time, and the machine failure is detected as soon as the failure takes place [4]. Jardine and Tsang [8] present a model to determine the optimal preventive replacement interval of a machine subject to breakdowns (also known as the group or block maintenance policy) minimizing the total expected replacement cost per unit time. This expected cost is obtained as a ratio of two expectations, total expected cost and total expected cycle length, based on a renewal process. In addition, they present two models to determine the optimal preventive replacement age of a machine subject to breakdown with and without taking into account the times required to perform corrective and preventive replacements. Abdel-Hameed [1] considers a periodic replacement policy with imperfect repairs. At failure, the decision consists in stating if the machine is restored to its condition prior to failure (minimal repair) or replaced. Ouali et al. [14] present a survey of replacement models with minimal repair. They consider preventive and corrective replacement policies where it is also possible to repair a failed machine without replacing it. The works described above use a cost function that includes the cost of performing the preventive and corrective maintenance, but the authors do not consider the cost related to waiting time to repair in the case where a failure occurs before the preventive maintenance, since it is assumed that the replacement is done instantaneously.

The motivation to include the waiting time in the cost function arises especially in the context of geographically distributed machines where the resources to perform the maintenance operations are limited. In works by Laggoune et al. [11], Zitrou et al. [23] and Berrade et al. [2] replacement and inspection models are taken into account in order to obtain optimal maintenance policies for a single machine subject to unforeseen failures, but they do not take into account the waiting time in their analysis. Crespo [5] classifies this time as a logistic delay which is the cumulative time in which maintenance cannot be performed due to the need of a resource which is lacking, traveling, or pending arrival of spare parts. For our problem, the waiting time is due to the technician who must travel to attend other machines scheduled before, according to a routing plan.

Different applications of maintenance operations tightly coupled with vehicle routing problems can also be found in the literature. Blakeley et al. [3] consider the problem of assigning preventive and corrective maintenance jobs to technicians and creating efficient daily routes to maintain and repair a set of elevators and escalators that are geographically distributed. They use a periodic vehicle routing problem formulation with a weighted objective function that includes workload balance, total travel distance/time, and overtime. Tang et al. [20] present a real-world