Journal of Rail Transport Planning & Management 3 (2013) 163–171

Contents lists available at ScienceDirect

Journal of Rail Transport Planning & Management

journal homepage: www.elsevier.com/locate/jrtpm

Optimal routing and scheduling of periodic inspections in large-scale railroad networks

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ARTICLE INFO

Article history:
Received 22 December 2013
Revised 21 February 2014
Accepted 24 February 2014
Available online 27 March 2014

Keywords:
Rail inspection
Scheduling
Periodic vehicle routing
Railroad maintenance
Heuristic
Local search

ABSTRACT

Railroads use a set of rail inspection teams to periodically examine the status of rail tracks across the railroad network. The rail inspection scheduling problem (RISP) is a large-scale routing and scheduling problem where thousands of inspection tasks are to be scheduled subject to many complex constraints. This paper proposes a vehicle routing problem formulation for RISP and develops a customized heuristic algorithm to effectively solve the problem. Real-world case studies show that the proposed approach significantly outperforms commercial solvers and the state-of-art manual solution approach. The proposed approach has been adopted by a Class I railroad to enhance safety and operational efficiency.

1. Introduction

Every year, North American railroads spend millions of dollars on periodic rail inspection. A fleet of rail inspection teams (including inspection vehicles and associated crews) travel on the railroad network and examine rail tracks for external and internal rail defects (such as kidney defects, wheelburn defect, head checking and squats) using visual inspection and technologies such as induction and ultrasonic devices (Cannon et al., 2003). According to the Federal Railroad Administration (FRA) Office of Safety Analysis (2014), track defects are one of the leading causes of train accidents in the United States. Among the 1747 train accidents that happened in 2012, 577 (or 33.03%) were caused by track defects, resulting in a total reportable damage of $102.9 million. Therefore, it is very important to optimally schedule the rail inspection so that the rail defects can be identified and repaired in time.

In practice, the railroad network is divided into hundreds of segments for the sake of rail inspection. Every segment should be inspected periodically at a certain frequency (which generally varies from once a few weeks to once a year) to ensure the safety of train operations. In this paper, we call each inspection activity a "task". A rail inspection schedule includes the assignment of tasks to inspection teams as well as the start times of the tasks such that all required inspection frequencies are satisfied. The routes of inspection teams should be optimized so that less time is spent traveling between tasks that may be a thousand miles apart. It should also satisfy a variety of other business constraints such as geographic preference, non-simultaneity and time window constraints. The scheduling horizon is normally short (e.g., a few weeks), while the schedule is updated frequently (sometimes daily) to address unexpected events (e.g., the delay of a task or the breakdown of a vehicle). Occasionally, long-term planning is also needed for resource allocation purposes (e.g., to determine the optimal number of inspection teams and to balance the workload throughout the year).

Practical rail inspection scheduling problem (RISP) instances are usually very large-scale and complex, involving hundreds or thousands of tasks, tens of inspection teams and thousands of business constraints. Current practice of the railroad industry mostly relies on the experience and judgment of experts. The solution process usually takes a long time but the solution quality may remain unsatisfactory. This paper, therefore, proposes a mathematical model and a solution algorithm to systematically and effectively solve RISP and help the railroads improve safety and operational efficiency.

The remainder of the paper is organized as follows. Section 2 reviews previous studies related to RISP. Section 3 presents a vehicle routing problem (VRP) based formulation of RISP. Section 4 presents the solution algorithms. Section 5 conducts case studies

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http://dx.doi.org/10.1016/j.jrtpm.2014.02.003
2210-9706/

with real-world data. Section 6 concludes the paper and discusses future research directions.

2. Literature review

Very limited research has been done on problems similar to RISP. Budai et al. (2006) solved a preventive maintenance scheduling problem where both short-duration routine activities and long-duration projects are scheduled on a single track segment, and hence no routing aspect was considered. Liebchen et al. (2007) discussed how a periodic event scheduling problem can be extended to address these aspects in railway timetabling; however, a complete model formulation or a solution algorithm was not presented in their paper. Morales et al. (2008) studied a similar geometry inspection scheduling problem which addresses not only the inspection frequency requirement, but also crew change point constraints and track restrictions (e.g., travel direction requirements, sharp-turn restrictions, and multiple tracks) for rail-bound inspection vehicles. The inspection territory of each vehicle was predetermined, and the model scheduled only one vehicle at a time. The model enumerated all possible day routes as decision variables, and could usually be solved by a commercial integer programming solver within 12 hours. What-if analysis was used to reassign territories among inspection teams in order to balance workload and improve the solution. Derinkuyu et al. (2010) presented a rail grinding scheduling problem and developed an optimization model whose objective was to minimize the deviations of grinding activities from a given set of desired maintenance frequencies. Retharekar and Mobasher (2010) presented a preventive maintenance scheduling problem. Constraints related to various factors such as train schedules and desired maintenance frequencies are considered. Heuristic algorithms were developed in the above two studies but the details were not disclosed.

Peng et al. (2010) and Peng and Ouyang (2012) studied track maintenance scheduling problems (TMSP) in a railroad network. Side constraints such as mutual exclusion and time window constraints were considered. The problems were formulated into time-space network models and were solved using multiple-neighborhood search. Their proposed approach has been applied in practice in the past few years. Both TMSP and RISP are routing and scheduling problems, where inspection or maintenance tasks across the network are scheduled in a horizon and are assigned to a set of teams. The two problems also have some similar side constraints such as time window constraints. However, they have two major differences which significantly affect the selection of model and algorithm. First, the durations of all tasks in TMSP in Peng et al. (2010) and Peng and Ouyang (2012) are integer numbers of weeks. The travel time between tasks occur during weekends and can be neglected in the schedule. As such, the scheduling horizon of TMSP can be naturally discretized into weeks, and solution approaches based on time-space networks and block interchange algorithms are suitable. In RISP, the tasks have continuous durations that range from less than an hour to a few weeks. The travel time, which could be as long as one day, must be incorporated into the schedule. Hence, it is very difficult to discretize the scheduling horizon in RISP. Second, TMSP is used for long-term planning and is solved infrequently (e.g., once a year), and a solution time of a few hours is often acceptable. However, RISP is usually solved much more frequently (e.g., weekly), and the user sometimes expects to see a solution within a few minutes for implementation in real time. A much faster algorithm is therefore needed.

Because of its routing aspect, RISP is very similar to a VRP problem (Dantzig and Ramser, 1959), where every task is located at a single vertex of the network. RISP also resembles an arc routing problem (ARP) (Orloff, 1974), where every task is represented by an arc instead of a vertex in the network. Some studies have investigated the periodic vehicle routing problems (PVRP) (Beltrami and Bodin, 1974; Christofides and Beasley, 1984; Chao et al., 1995; Cordeau et al., 1997; Francis et al., 2008). In the standard PVRP, every customer must be periodically visited, (which is similar to the frequency requirements in RISP) according to a predetermined service frequency and a set of candidate schedules. Heuristic algorithms have been widely applied to PVRP. For example, Christofides and Beasley (1984) proposed a two-stage heuristic, where the first stage constructed an initial solution, and the second stage used an interchange procedure to improve the solution. Francis et al. (2006) introduced the concept of service choice, where the service frequency of a customer is no longer fixed, and candidate schedules with higher frequencies are allowed. The model was solved using Lagrangian relaxation combined with a branch and bound procedure. Other studies on PVRP include Alonso et al. (2008) and Coene et al. (2010), where algorithms such as tabu search and Lagrangian relaxation were proposed. A comprehensive review of PVRP can be found in Campbell and Wilson (2014).

One limitation of the standard PVRP is that a set of candidate schedules must be predetermined. If the time for a customer to be visited is flexible, an exponential number of candidate schedules will be required. Gaudioso and Paletta (1992) and Maya et al. (2012) studied another type of PVRP where a customer requires a certain number of visits in a given period (e.g., once or twice a week). These models do not need a set of candidate schedules as the input, but the scheduling horizon was still discretized into intervals (e.g., days). A set of binary variables were used to represent whether or not a customer is served on a certain day. For RISP, however, the horizon cannot be discretized. First, an inspection activity may last from less than one hour to a few weeks. An activity is often interrupted at the end of a day (e.g., based on crew working hours) and be resumed at the beginning of the next day. Second, there is no depot in RISP. Every day an inspection team starts working from its previous day's end location. Therefore, the multi-day activities should be planned as one whole route over the continuous scheduling horizon, and it is not clear how the standard PVRP models can be directly applied.

3. Problem formulation

In this section, we will formulate the optimization problem in order to give a precise description of RISP. We will first present a VRP model for RISP, and then introduce different types of side constraints and costs.

3.1. Vehicle routing problem model

Let S be the set of track segments to be inspected periodically. Because a segment may be inspected multiple times in the scheduling horizon, we define a task as a single inspection activity on a segment. So each segment $s \in S$ has a set of tasks $I_s = \{i_{s1}, \ldots, i_{s|I_s|}\}$ to be scheduled at or after the beginning of the scheduling horizon, and also a most recently started task i_{s0} which has started prior to the beginning of the scheduling horizon. For $a = 1, \ldots, |I_s|$, we always let task $i_{s(a-1)}$ be performed before i_{sa}. Let $I = \cup_{s \in S} I_s$ be the set of all tasks to be scheduled.

When performing a task $i \in I$, the inspection team starts from one location of the segment, moves along the track, and completes the task at another location. There may be multiple ways to perform a task, each with different start location and end location. For example, to inspect a single-track segment between locations A and B, a team may move from A to B or from B to A. To inspect a double-track segment between A and B, a team may make a