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Optimizing road network daily maintenance operations with stochastic service and travel times

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A B S T R A C T

This paper studies optimization methods for a routing problem encountered in daily maintenance operations of a road network. Stochastic service and travel times on road segments are considered. The problem is formulated as a variation of the capacitated arc routing problem (CARP). A chance-constrained programming model is firstly developed and solved by a branch-and-cut algorithm. A stochastic programming model with recourse is also proposed to take into account the recourse costs in case of route failure. The problem is solved by an adaptive large neighborhood search algorithm. The computational experiments demonstrate the effectiveness of the algorithm.

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1. Introduction

The total length of the elevated ways and freeways in Shanghai is more than 200 km. The daily maintenance of this road network is a significant challenge to the transportation agency of the city. The daily maintenance operations include visually checking the operational status of each segment, evaluating the function of the auxiliary facilities, reporting the defects of the road and so on. Under the increasing pressure of high demand for improved road safety and mobility, and tight budget constraints, the road network maintenance authority is now seeking efficient methods to optimize its daily operations. The situation becomes even more challenging when considering stochastic service and travel times on road segments. Conventional approaches to the daily maintenance decision problem are highly empirical in nature. Decisions pertaining to when and where to deploy service vehicles are typically made by a supervisor, based mostly on service time forecast, and personal experience. As such, it is not only difficult to compare alternative monitoring plans, but also to adjust the monitoring plan properly when service times vary from forecasts.

The optimization problem in the context of road network daily maintenance can be briefly described as follows. Within each day, some segments of the entire road network need to be monitored. The road monitoring is carried out by a fleet of vehicles. A particular monitoring service is associated with an estimated service time. Each segment of road is associated with a stochastic travel time. The problem consists of determining a set of monitoring routes of minimum cost such that a monitoring route starts and ends at the depot, each required segment of road is serviced on one of the routes, and total

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service duration of each monitoring vehicle does not exceed a given threshold. Weather or traffic conditions may result in uncertainty of travel times on a road. Furthermore, actual service times may be radically different from the estimated times, due to road conditions, accidents, technician's skills, and so on. For example, the service may be delayed on a particular segment of road because of unexpected situations. This uncertainty on one road segment can result in a large delay for road segments scheduled later for the same monitoring vehicle. Therefore, it becomes important to construct vehicle routing strategies that will be efficient even in presence of uncertainty in both travel and service times.

This problem is a typical application of the capacitated arc routing problem (CARP). We formulate it as a CARP with Stochastic Service and Travel Times (abbreviated as CARP-SSTT). The CARP was introduced by Golden and Wong (1981) and can be briefly defined as follows: given a fleet of identical vehicles of a given capacity and an undirected graph with non-negative edge demands and edge costs, find a set of minimum cost routes for the vehicles that service all the positive-demand edges. Each route must contain the depot, and the total demand that a vehicle services cannot exceed its capacity.

Since then, the CARP has been widely studied in the literature (see the surveys in Assad and Golden, 1995; Corberán and Princ, 2010). However, one practical aspect that has seldom been addressed is stochastic travel times on the edges. More precisely, a stochastic travel time is associated with each edge, which can be a continuous or discrete random variable. Ignoring these travel time variations when formulating the CARP may result in suboptimal or even infeasible solutions in real situations.

This paper is organized as follows. Section 2 presents a brief literature review dedicated to routing problems with stochastic variables. Section 3 presents two types of stochastic models for the CARP-SSTT, one of which is a chance-constrained programming model. The other one is a stochastic programming model with recourse. A branch-and-cut algorithm is presented in Section 4 to solve the chance-constrained programming model optimally. Section 5 introduces an adaptive large neighborhood search algorithm. Section 6 reports the experimental results. Finally, Section 7 concludes the paper and proposes future research directions.

2. Literature review

While considerable research has been devoted to the general CARP, research in the CARP with stochastic parameters is scarce. Fleury et al. (2004) consider the CARP with stochastic demands. A memetic algorithm is adapted to handle the randomness of the demands. Fleury et al. (2005) evaluate the robustness of the CARP solutions against demand fluctuations and to see how this robustness can be improved. Christiansen et al. (2009) address the CARP with stochastic demands that follow a Poisson distribution. The objective is to find a collection of routes with minimum expected cost. The problem is solved exactly by a branch-and-price algorithm, and the stochastic nature of the demand is incorporated into the pricing problem. Laporte et al. (2010) study the CARP with stochastic demands in the context of garbage collection. An adaptive large-scale neighborhood search heuristic is developed to construct a solution that takes into account the expected cost of recourse.

Tagmouti et al. (2007) study the CARP with time-dependent service costs. The service costs on the required arcs are defined as piecewise linear functions of the time. This work is motivated by winter gritting applications. The problem is transformed into an equivalent node routing problem, and solved by a column generation approach. Tagmouti et al. (2011) extend this study by considering a dynamic variant of the problem, where the service cost functions on the required arcs are updated according to the weather forecast. A variable neighborhood descent (VND) heuristic is developed and adapted to dynamic situation.

So far, no work has been found on the CARP with stochastic travel times. There exists some research for the Vehicle Routing Problem with Stochastic Travel Times (VRP-STT), which is the node routing counterpart of the arc routing problem with stochastic travel times. Gendreau et al. (1996) survey the literature on VRP with stochastic elements, namely stochastic demands and stochastic travel times. They outline the basic solution concepts and methodologies for each specific type of problems.

Some works model the travel time as time dependent, and define the travel time as a piecewise or a continuous function of the time of a day. Malandraki and Daskin (1992) study the time-dependent VRP. The travel time between each pair of nodes is represented as a step function within each time intervals. Nearest neighbor heuristics and a cutting plane heuristic are presented to solve the problem. Ichoua et al. (2003) develop a model to calculate the travel time taking into account the travel speed when the vehicle crosses a boundary between two time periods. Thus, the travel time is a piecewise continuous function over time. Using a similar methodology, Haghani and Jung, 2005 treat the travel time as a continuous function, and thus can accept any kind of travel time variation. Real-time service requests are also considered in their work. A genetic algorithm is used to solve the problem, and its performance is compared with a lower bound. Fleischmann et al. (2004) describe the derivation of travel time data from modern traffic information systems, and present a general framework for the implementation of time-varying travel times in various vehicle-routing algorithms.

Some other works treat the travel time as a random variable that follows a probability distribution. Kao (1978) proposes two solution approaches, based on dynamic programming and implicit enumeration, to solve the traveling salesman problem with stochastic travel times, a special case of the VRP-STT. The objective is to find a tour that has the greatest probability of completion by a specified deadline C. In a subsequent study by Sniedovich (1981), the dynamic programming approach is shown to be effective for obtaining close-to-optimal solutions when the problem is monotonic. The monotonicity condition can be expressed as follows. If the salesman is in city i at stage k, he must select the next destination in such a way that, whatever the city leading into i, the selection constitutes an optimal choice. Laporte et al. (1992) consider the VRP with stochastic service and travel times, in which vehicles incur a penalty proportional to the duration of their route in excess of a preset constant. A chance-constrained programming model and two different recourse strategies are developed. Kenyon and

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