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A robust optimization approach for the road network daily maintenance routing problem with uncertain service time

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ABSTRACT

This paper studies the robust optimization approach for the routing problem encountered in daily maintenance operations of a road network. The uncertainty of service time is considered. The robust optimization approach yields routes that minimize total cost while being less sensitive to substantial deviations of service times. A robust optimization model is developed and solved by the branch-and-cut method. In computational experiments, the behavior of the robust solutions and their performance are analyzed using Monte Carlo simulation. The robust optimization model is also compared with a classic chance-constrained programming model. The experimental analysis provides managerial insights for decision makers to determine an appropriate routing strategy.

1. Introduction

The problem studied in this paper concerns the routing problem faced by a road network monitoring service, where each day a part of the road network needs to be monitored by a fleet of vehicles. Monitoring operations include visually checking the operational status of each road segment, evaluating the function of the auxiliary facilities, reporting the defects of the road and so on. An estimated service time is associated with each request for monitoring service on a road segment. A travel time is associated with each segment of road. The problem consists of determining a set of minimum cost monitoring routes where each required segment of road is serviced on one of the routes.

In the case of road monitoring, the estimated service time can be radically different from the actual service time, due to road conditions, accidents, technician's skills, and so on. 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 in presence of uncertainty in service time.

This work is motivated by a real transportation service application where each day a network of high-speed freeways needs to be monitored by vehicles from different maintenance stations in a large urban setting. In this application, about 50% of the monitoring requests have estimates for service time that significantly differ from actual monitoring times. The problem has been addressed by Chen et al. (2014) as a variant of the Capacitated Arc Routing Problem (CARP), in which strong assumptions were made regarding the distribution of service times. Chen et al. (2014) focus on optimizing expected total service cost and analyze the performance of a routing policy based on expected objective value. In this paper, we use the robust optimization methodology to formulate the problem, which allows us to consider the risks associated with extreme

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outcomes. The objective is to obtain a solution that optimizes the worst-case value over all data uncertainty while not being overly conservative. We also present a comparison with a chance-constrained method to illustrate the differences with the robust optimization approach. The differences are important in determining which strategy is better to apply under a specific situation.

This paper is organized as follows. Section 2 presents a brief literature review. The robust formulation of the problem is described in Section 3. A branch-and-cut algorithm is presented in Section 4 to solve the robust optimization model optimally. Section 5 reports experimental results. Finally, Section 6 concludes the paper and proposes future research directions.

2. Literature review

We review in the three following subsections respectively the works on the Arc Routing Problem (ARP) with stochastic parameters, on the VRP with stochastic times, and on robust optimization.

2.1. ARP with stochastic parameters

Despite numerous publications dealing with efficient scheduling methods for the ARP, very few addressed the inherent stochastic and dynamic nature of problem parameters. 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 CARP solutions against demand fluctuations and examine 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. (2011) study a dynamic variant of the ARP, in which the service cost is time dependent. The problem is motivated from winter road gritting service. A variable neighborhood descent (VND) heuristics is developed and adapted to the dynamic situation, where the service time functions on the required arcs are updated according to weather reports.

2.2. VRP with stochastic times

To the best of our knowledge, no work dealing with the ARP with stochastic travel times has appeared in the literature. There exist, however, some papers that address the Vehicle Routing Problem with Stochastic Travel Times (VRP-STT), the node routing counterpart of the arc routing problem with stochastic travel times. Gendreau et al. (forthcoming) survey the literature on VRP with stochastic elements, namely stochastic demands, stochastic customers, and stochastic service and travel times.

Some papers 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 travelling 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. 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 Morton (2003) study the same problem as Laporte et al. (1992). They provide conditions under which the stochastic problem reduces to a simpler deterministic problem and give bounds on the optimal solution. A branch-and-cut algorithm is embedded within a Monte Carlo solution procedure for solving the VRP with stochastic travel and service times. Li et al. (2010) study the VRP with stochastic travel times and time windows. It is assumed in their work that the travel time is a continuous random variable with normal distribution. A chance-constrained programming model and a stochastic programming model with recourse are proposed to formulate the problem. Zhang et al. (2012) assume that the travel time on each arc follows a normal distribution, and formulate the problem as a chance-constrained programming model. A scatter search approach and a genetic algorithm are developed to solve this model. Jaillet et al. (2013) study the routing problems on networks with deadlines imposed on some nodes. Uncertain travel times are considered and characterized by exact distributions, or by a distributional uncertainty set incorporating ambiguity. Algorithms with decomposition techniques are developed to find optimal routing policies such that arrival times at nodes respect deadlines "as much as possible".

Queuing approaches have also been applied to model the stochastic travel time or travel speed of vehicles. Van Woensel et al. (2008) introduce the traffic congestion component in the standard VRP based on queuing theory. Results show that explicitly taking into account congestion during the optimization results in routes that are considerably shorter in terms of total travel time. In Lecluyse et al. (2009), the travel speed in each time period is also obtained by applying queuing theory to traffic flows.