Dynamic routing for milk-run tours with time windows in stochastic time-dependent networks

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ABSTRACT

We consider finding static yet robust recurring milk-run tours while dynamically routing the vehicle between site visits. The network arcs experience recurrent congestion, leading to stochastic and time-dependent travel times. Based on vehicle location, time of day, and current and projected network congestion states, we generate dynamic routing policies (DRP) for every pair of sites using stochastic dynamic programming (SDP). By simulating DRP we find travel time distributions for each pair of sites which is used to build the robust tour using another SDP formulation. Results are very promising when the algorithms are tested in a simulated network using historical traffic data.

1. Introduction

Just-in-time (JIT) production requires frequent small-batch pickups and deliveries subject to fixed time windows. Since the shipments are usually less than a truckload, the freight carrier planners develop milk-run tours (e.g., a visiting sequence of pickup and delivery sites). In a milk-run tour, for example, the vehicle departs from a distribution center (DC), picks up goods from several supplier sites, and returns to the DC for another delivery. In planning milk-run tours, managers also consider heijunka (production smoothing or workload leveling) and muda (waste) philosophies of JIT production. Whereas the former can be achieved by equally spacing the delivery time windows over the suppliers’ operating hours, the latter can be achieved by visiting the supplier sites at an optimal frequency, balancing transportation and inventory costs. The recurrent and non-recurrent congestion on road networks increase the travel time variability thus rendering it difficult to make delivery and pickup visits within the established time windows, which can be as narrow as 15–30 min (Chen et al., 2003; Groenevelt, 1993). Some industries allow early or tardy delivery and/or pickups with a penalty (soft time windows). However, there are many practical settings (e.g., JIT production) with hard time windows where vehicles may pick up or deliver only during fixed times without exception (Cordeau et al., 2000).

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1 For carriers, as congestion worsens the costs related to travel time (e.g. labor and overtime costs) may outweigh other operating costs (e.g. vehicle miles traveled) (Fugilezzi, 2010).

2 A survey in California found that 85% of trucking companies miss their time window schedules due to road network congestion. Furthermore, 78% of the managers surveyed stated that the time-window schedules for pickup and deliveries force their drivers to operate under congested road network conditions (Golob and Regan, 2013).

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In this paper, we address the problem of planning milk-run tours for JIT production subject to hard time windows in congested road networks. We model the milk-run tours as Traveling Salesman Problems (TSP) with hard time windows. The road network congestion is represented through random network arc travel times and time-dependent congestion states.

The classical TSP is concerned with finding the least cost tour that visits each site exactly once given the set of sites. The travel between any pair of sites is a path which can be static (e.g., a fixed sequence of arcs) or can be determined through a dynamic policy. The cost of travel between pairs of sites can be measured in time, distance or a function of both, be deterministic or probabilistic, and be time-dependent or independent. In STD-TSP setting, we consider a TSP with hard time windows under stochastic time-dependent (STD) arc travel times. To the authors’ best knowledge, the preceding TSP literature assumes that the path travel cost between pairs of sites is either deterministic or stochastic with a known probability distribution, i.e. exogenously determined path travel cost distributions. In our network setting, the path travel times are both stochastic and time-dependent. We determine the distributions of these path travel times through optimal dynamic routing on network arcs using the real-time traffic information (e.g., speed data) available from the Intelligent Transportation System (ITS) sensor network. In optimal dynamic routing between pairs of sites, we consider only the recurrent congestion (e.g., rush hour) and exclude the non-recurrent (e.g., traffic incidents and inclement weather). This is necessary since the milk-run TSP tours are established for longer periods where the recurrent congestion is more dominant. We model the recurrent congestion by defining congestion states of arcs based on historical ITS traffic data using Gaussian Mixture Model (GMM) based clustering (Verbeek et al., 2003). The changes in arc congestion states represent the traffic dynamics and are modeled as Markov processes. Accordingly, the optimal dynamic routing problem is then cast as a Markov decision process (MDP) where the states space consists of the position of the vehicle, the time of the day, and the current and projected congestion states of arcs with limited look ahead (examining the state of the full network is computationally prohibitive and even unnecessary, see Kim et al., 2005b). We identify the paths’ optimal dynamic routing policies (DRP) by solving a stochastic dynamic programming formulation for each pair of sites.

By simulating the optimal DRPs, we estimate the travel time distributions between every pair of sites. We then use these distributions to determine the optimal TSP tour by solving a stochastic dynamic programming formulation for TSP. Since the travel times are STD, we employ the convolution approach in Chang et al. (2009) to estimate the distribution of site arrival times for pickup and delivery. Whereas the routes between pairs of sites are dynamic, the TSP tour is static. This is because, in JIT production systems, the tours for pickups and deliveries support such objectives as production smoothing and workload leveling and remain fixed for extended periods (e.g., months). An optimal TSP tour can be obtained by minimizing the mean criteria combination (e.g., travel time, mileage, and truck utilization) or a mean-variance objective that also accounts for the variability of criteria. Although our methodology could accommodate a wide range of these objectives, we select a mean-variance objective based on the trip time which accounts for the transportation cost and service level (i.e., on-time performance) trade-offs in JIT production systems. We define the most robust TSP tour as the tour with minimum trip time mean-variance objective.

Our study contributes to the stochastic TSP literature in several ways. First, different than existing stochastic TSP studies, by dynamically routing between pairs of sites, we determine the path travel cost distributions between pairs of sites endogenously. With time-dependent travel times, our results show that this distinction results in selecting optimal tours that are superior than those found by considering static paths between pairs of sites in terms of cost and on-time performances. Second, we propose a robust tour formulation that selects tours based on a preset trade-off between mean and variance of the cost performance. Third, we propose a procedure to set time-windows for milk-run tours to support JIT deliveries which improves the on-time performance. Lastly, we demonstrate the proposed model and methodology using real-world network and traffic data sets.

These contributions can be summarized as follows:

- Integrating dynamic routing within stochastic TSP to determine robust milk-run tours on STD networks and the analysis of cost and on-time performance improvement of dynamic routing over static routes between milk-run sites.
- Introduction of robustness measure for selecting tours in stochastic networks and a procedure to set time-windows for milk-run tours in STD networks to improve the on-time performance.
- Using real network and traffic data, simulating the results of the proposed integrated approach and demonstrate the transportation cost and delivery service level improvement based on optimal dynamic routing between sites.

The rest of the paper is organized as follows. A selective survey of the related literature is given in Section 2. In Section 3, the modeling of the stochastic time-dependent TSP is described. Section 4 presents the experimental results of a case study application to show the effectiveness of the proposed approach. Section 5 concludes the study and suggests directions for future research.

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3 According to Research and Innovative Technology Administration (RITA) of U.S. Department of Transportation (US DOT), “Intelligent transportation systems (ITS) encompass a broad range of wireless and wire line communications-based information and electronics technologies. When integrated into the transportation system’s infrastructure, and in vehicles themselves, these technologies relieve congestion, improve safety and enhance productivity.” ITS technology and coverage is expanding quickly in the U.S. and is widely used in many developed and developing nations around the world. For more information about U.S. ITS, see: http://www.its.dot.gov.
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