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Discrete Optimization

On service consistency in multi-period vehicle routing

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ABSTRACT

In this paper, we investigate a new variant of the vehicle routing problem (VRP), termed the *multi-period vehicle routing problem with time windows and limited visiting quota* (MVRPTW-LVQ), which requires that any customer can be served by at most a certain number of different vehicles over the planning horizon. We first formulate this problem as a mixed integer programming model and then devise a three-stage heuristic approach to solve the problem. Extensive computational experiments demonstrate the effectiveness of our approach. Moreover, we empirically analyze the impacts of varying the levels of service consistency and demand fluctuation on the operational cost. The analysis results show that when demand fluctuation is relatively small compared to vehicle capacity, enforcing consistent service can increase customer satisfaction with only a slight increase in the operational cost. However, when a vehicle can only serve a small number of customers due to its capacity limit, relaxing the service consistency requirement by increasing the value of the visiting quota could be considered.

1. Introduction

In delivery services, significant emphasis has been placed on *service consistency* such that deliveries to regular customers are made at approximately the same time of the day, and by the same deliveryman or deliverymen. Punctually keeping a regular schedule increases customer satisfaction since it allows the customer to plan for deliveries during their working day with confidence. Furthermore, having the same person or persons performing the deliveries can help develop customer relationships, and this familiarity can also increase the efficiency of the service.

However, delivery schedules with high service consistency would incur additional operational costs when there is a significant *demand fluctuation* for the services (i.e., the amount of goods to be delivered changes substantially each day) compared with the vehicle capacity. Due to vehicle capacity limitation, a deliveryman might be unable to fulfill the delivery requests of all customers on his regular route if the amount of goods demanded is particularly large on that day. In general, there are two ways to handle this situation. One is to reduce the number of customers on the regular route of each deliveryman so that the maximum demand can always be handled by a single vehicle, but this is likely to increase manpower requirements. The other is to allow a few different deliverymen to service each customer, which dilutes the benefits of service consistency.

In this paper, we consider the *multi-period vehicle routing problem with time windows and limited visiting quota* (MVRPTW-LVQ). Given a set of customers with requests for the delivery of goods within time windows over a period of D days, the task is to find a set of vehicle routes that fulfill all requests using the minimum number of vehicles and with the minimum total travel distance; this is a combination of the multi-period vehicle routing problem (MVRP) and the vehicle routing problem with time windows (VRPTW). Service consistency is controlled by the limited visiting quota (LVQ), which states that any particular customer can only be serviced by at most R different vehicles over the entire planning horizon. This problem was first introduced by Zhu, Zhu, Che, and Lim (2008), who build an application for the problem for one of the largest food and restaurant chains in Hong Kong and proposed a decomposition approach which first iteratively solves a series of VRPTWs with a state-of-the-art VRPTW solver proposed by Lim and Zhang (2007) and then combines the resulted VRPTW solutions into an MVRPTW-LVQ solution. The MVRPTW-LVQ is also related to the consistent vehicle routing problem (ConVRP) proposed by Groër, Golden, and Wasil (2009), which requires that each customer may only be visited by one vehicle (i.e., $R = 1$) and also includes some additional constraints.

We propose a three-stage approach to solve the MVRPTW-LVQ. Stage one involves finding high-quality initial solutions fast using the decomposition algorithm proposed by Zhu et al. (2008) with a much simpler but faster VRPTW solver. Stage two attempts to reduce

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the number of vehicles in the solution by employing a repair procedure in a tree search algorithm. Stage three performs a tabu search post-optimization procedure that focuses on reducing the total travel distance. Computational experiments on benchmark data show that our Decomposition, Repair and Distance Reduction (DRDR) approach outperforms the approach proposed by Zhu et al. (2008) on five out of the six benchmark data sets. We also modify our approach to handle the ConVRP; this resulting algorithm outperforms two existing ConVRP approaches on average on benchmark data. These experiments demonstrate the ability and robustness of our approach in handling consistency service in the VRP with multiple periods.

We obtained several interesting findings from experiments using the DRDR approach to analyze the effects of demand fluctuation on operational cost given different service consistency requirements. A maximally consistent routing plan can be generated by setting the LVQ value to 1, i.e., $R = 1$. Our experimental results show that when the vehicle capacities are small in relation to the amount of goods demanded, the benefit of relaxing the service consistency requirement (e.g., setting $R = 2$) results in a significant reduction to the operational cost. This finding suggests that in applications where the demand fluctuation is relatively large compared to the vehicle capacity, such as the delivery of inventory restocks to retail chain outlets, demand fluctuation can significantly increase the operational cost of a rigidly consistent routing plan. Managers should therefore consider relaxing the service consistency requirements in order to balance the trade-off between service level and operational cost. In contrast, when the vehicle capacities are relatively large (thereby reducing the impact of demand fluctuation), a deliveryman can be assigned to serve relatively more customers on his regular route, and there is little impact on the total operational cost when enforcing stronger service consistency requirements. Applications of this type, such as the small package shipping industry, can therefore place more emphasis on service consistency to increase operational efficiency from familiarity and facilitate cooperation between deliverymen and customers.

The main contributions of this paper are as follows. First, we provide a strong mixed integer programming model for the MVRPTW-LVQ for the first time. Second, we propose a three-stage approach to solve the problem, whose effectiveness can be demonstrated by a set of computational results. Third, we analyze the trade-off between service consistency and operational cost under different scenarios, which provides managerial insights for the industry.

The remainder of the paper is organized as follows. In Section 2, we provide an overview of the related existing literature. We then present a formal description of our problem in Section 3, as well as a mixed integer programming (MIP) model. Our three-stage solution approach is described in Section 4. We present our computational results in Section 5, which includes experiments for parameter tuning, component tests and the instances of both the MVRPTW-LVQ and the ConVRP. Section 6 provides an analysis of the trade-off between service consistency and demand fluctuation on operational cost. Finally, we conclude our article in Section 7 with some closing remarks.

2. Literature review

The periodic vehicle routing problem (PVRP), also known as the period vehicle routing problem, is a variant of the classical vehicle routing problem (VRP) in which delivery routes are constructed over a period of time (e.g., multiple days). It occurs in many practical applications, such as food distribution (Zhu et al., 2008) and the soft drink industry (Golden & Wasil, 1987). Consequently, the PVRP and its variants have received considerable attention from the research community, where the use of meta-heuristics has been shown to be an effective solution approach, e.g., tabu search (Cordeau, Gendreau, & Laporte, 1997) and variable neighborhood search (VNS) (Hemmelmayr, Doerner, & Hartl, 2009). We refer the reader to Francis, Smilowitz, and Tzur (2008) for an extensive overview of the PVRP and its variants.

In certain practical PVRP applications, service consistency is a significant factor. The use of time windows, where vehicles must arrive at each customer location within a specified time range, can indirectly influence the service consistency of a routing plan. The VRP variant that considers time windows has been widely studied in literature. Various meta-heuristic approaches have been developed to tackle the VRPTW, such as evolutionary algorithms (Nagata, Bräysy, & Dullaert, 2010) and local searches (Lim & Zhang, 2007). Although only a single period is considered in the VRPTW, solution approaches for the VRPTW with slight modifications can also be applied to the multi-period vehicle routing problem with time windows (MVRPTW), e.g., the solution approaches proposed by Cordeau, Laporte, and Mercier (2001, 2004).

Various other methods have also been tried in existing literature to include service consistency into the route planning process. For example, Zhong, Hall, and Dessouky (2007) investigated a problem where drivers should be consistently assigned to the same territories so as to improve driver performance due to familiarity; for simplicity, time windows and vehicle capacities were not considered. The authors proposed a two-stage learning/forgetting model, where service consistency is set as a soft constraint, to construct core service territories in the strategic level and allocate customers in the non-core territories each day. Another example is the *periodic vehicle routing problem with service choice* (PVRP-SC) proposed by Francis, Smilowitz, and Tzur (2006), where the service frequency of customers and delivery demand are decision variables and the objective function balances travel time and service benefit. Francis and Smilowitz (2006) presented a continuous approximation model for the PVRP-SC and Francis, Smilowitz, and Tzur (2007) analyzed the trade-offs between operational complexity and flexibility in both the PVRP and the PVRP-SC. Operational complexity is defined as the difficulty of implementing a solution to the problem and is quantified using three measures, namely driver coverage, arrival span and crew size. Although the crew size is similar to the LVQ, it was simply analyzed in two cases, i.e., consistent planning and non-consistent planning. Recently, Coelho, Cordeau, and Laporte (2012) considered in a multi-vehicle inventory routing problem six different inconsistency features, which are quantity consistency, vehicle filling rate, order-up-to policy, driver consistency, driver partial consistency and visit spacing. Moreover, Smilowitz, Nowak, and Jiang (2013) incorporated workforce management into periodic delivery operations, where two measures, namely customer familiarity and region familiarity, are used to evaluate the consistency of workforce management.

The problem investigated in this study presents a more direct method of including service consistency into the planning process. The service consistency is ensured by a limited visiting quota (LVQ) hard constraint requiring that each customer can only be visited by at most R different vehicles over the entire planning horizon. The LVQ constraint was first introduced by Zhu et al. (2008) for an application that schedules food delivery to stores for one of the largest food and restaurant chains in Hong Kong. Service consistency is particularly important for this application not only to facilitate effective communication and coordination between the deliverymen and store employees, but also because most of the retail stores are located in subway stations and shopping malls, so finding parking spaces and store locations can be a challenge if the deliveryman is unfamiliar with the environs. The LVQ constraint explicitly addresses this issue by specifying the value of R, i.e., the necessary level of service consistency.

When the LVQ value is set to $R = 1$, the resultant problem is similar to the consistent vehicle routing problem (ConVRP) proposed by Groër et al. (2009). The ConVRP models a situation found in the small package shipping industry, where the fostering of customer relations