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A parallel simulated annealing method for the vehicle routing problem with simultaneous pickup–delivery and time windows

Chao Wang [a], Dong Mu [a,*], Fu Zhao [b,c], John W. Sutherland [b]

[a] School of Economics and Management, Beijing Jiaotong University, Room 718, Si Yuan Dong Lou, No. 3 Shang Yuan Cun, Hai Dian District, Beijing 100044, China
[b] Environmental and Ecological Engineering, Purdue University, Potter Engineering Center, Room 364, 500 Central Drive, West Lafayette, IN 47907, United States
[c] School of Mechanical Engineering, Purdue University, ME 2194, 585 Purdue Mall, West Lafayette, IN 47907, United States

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A B S T R A C T

This paper addresses a variant of the vehicle routing problem in which customers require simultaneous pickup and delivery of goods during specific individual time windows (VRPSPDTW). A general mixed integer programming model is employed to minimize the routing cost due to: the cost of vehicles and the travel cost of vehicles. A parallel Simulated Annealing (p-SA) algorithm that includes a Residual Capacity and Radial Surcharge (RCRS) insertion-based heuristic is developed and applied to solve this NP-hard optimization problem. Computational results are reported for 65 test problems from Wang and Chen's benchmark and compared with the results from a Genetic Algorithm (GA) that minimizes the number of vehicles (NV) as the primary objective. Experimental results demonstrate the effectiveness of the p-SA algorithm, which is able to achieve the same objective response as 100% of the Wang and Chen small-scale benchmarks (number of customers from 10 to 50). For the Wang and Chen medium-scale benchmarks (number of 100 customers), the p-SA algorithm obtains better NV solutions for 12 instances and the same NV solutions for the remaining 44 instances. For the 44 instances with the same NV solutions, a secondary objective, travel distance (TD), the p-SA provides better solutions than the GA for 16 instances, and equal solutions for 7 instances. In addition, solutions are found for 30 large-scale instances, with customers of 200, 400, 600, 800 and 1000, which may serve as a new benchmark for the VRPSPDTW problem.

1. Introduction

Owing to fossil fuel consumption and airborne emissions, freight transportation has a significant effect on the environment. In the U.S, truck freight transportation is the dominant domestic freight mode and optimization of truck routing and scheduling will reduce the environmental impact of this sector. Many enterprises have initiated efforts to incorporate reverse logistics into their regular delivery and distribution systems to reduce costs associated with energy consumption, and satisfy applicable regulations and laws (Dethloff, 2001; Wang & Hsu, 2010). Such an integrated system has found applicability in a wide variety of fields such as library books distribution (Min, 1989), grocery distribution system (Zachariadis, Tarantilis, & Kiranoudis, 2009), parcel delivery (Berbeglia, Cordeau, & Laporte, 2010), and home health care service (Liu, Xie, Augusto, & Rodriguez, 2013). In the literature, this problem has attracted research interest because it models a wide variety of business operations involving bi-directional flow of goods, and has been referred to as the pickup and delivery problem (PDP). Toth and Vigo (2002), and Berbeglia, Cordeau, Gribkovskaia, and Laporte (2007) have provided excellent surveys of models for the PDP. The PDP can be divided into four situations: (i) delivery-first, pickup-second for the vehicle routing problem with backhauls (VRPB), e.g. (Goetschalckx & Jacobs-Blecha, 1989; Salhi & Nagy, 1999), (ii) simultaneous pickups and deliveries for the vehicle routing problem with simultaneous pickup and delivery (VRPSPD), e.g. (Min, 1989), (iii) mixed deliveries and pickups for the vehicle routing problem with mixed pickup and delivery (VRPMPD), e.g. (Nagy & Salhi, 2005; Wassan, Wassan, & Nagy, 2008), and (iv) inter-related pickups and deliveries for the dial-a-ride problem, e.g. (Diana & Dessouky, 2004; Lu & Dessouky, 2004).

This paper investigates an extended situation of the VRPSPD problem, in which enterprises allow customers to request their goods to be delivered and picked up within pre-defined time

* Corresponding author at: Room 718, Si Yuan Dong Lou, Beijing Jiaotong University, No.3 Shang Yuan Cun, Hai Dian District, Beijing 100044, China. Tel.: +86 138 0129 2938.

E-mail addresses: chaowang.hn@gmail.com (C. Wang), mudong.bjtu@gmail.com (D. Mu), fzhao@purdue.edu (F. Zhao), jwsuther@purdue.edu (J.W. Sutherland).

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windows in order to provide satisfactory service (Wang & Chen, 2013). In the literature this problem is usually termed the vehicle routing problem with simultaneous pickup and delivery and time windows (VRPSPDTW). Time windows define the earliest and latest time that a vehicle may arrive at a customer and start service. A soft time window is nonbinding and there is no penalty on violation. On the other hand, a hard time window cannot be violated, i.e., if a vehicle arrives before the time window opens, it must wait until the time window opens; and it is not allowed to arrive after the time window has closed. In this paper hard time windows are considered. The VRPSPDTW problem involves a fleet of homogenous or non-homogenous vehicles stationed at a depot to serve different geographically scattered customers. The vehicles are not only required to deliver goods from the depot to customers but also simultaneously to pick up goods at the customer locations for return to the depot, without violating vehicle capacity constraints and the defined time windows specified by the customers.

The VRPSPDTW is an NP-hard combinatorial optimization problem (Wang & Chen, 2012) since it can be reduced to a VRPSPD (which is NP-hard) problem when all the customers' earliest service times are equal to the depot's open time, and the latest service times are equal to the depot's closing time. Since VRPSPDTW is NP-hard, exact algorithms can only be used to find solutions for small-and-medium scale instances. The commercial linear programming software CPLEX has been reported to solve the VRPSPDTW problem executed on an Intel Core2 Quad 2.4G computer with 1G memory, and was only able to solve a 10 customer instance, and a portion of the 25 and 50 customer scenarios (Wang & Chen, 2012). For the solved 50 customers instance, the computation time was 327,404 s. Therefore, large-scale instances of VRPSPDTW cannot be solved by exact solution methodologies within an acceptable computational time. Due to the computational challenge associated with applied problems that involve large numbers of customers, researchers and practitioners are usually interested in developing heuristic or meta-heuristic approaches to produce high-quality solutions (but not necessarily optimal solutions) with reasonable computational times. Among the solution methods for VRP and its variants, parallel heuristic and metaheuristic methods have emerged in recent years (Jin, Crainic, & Løkketangen, 2012). Unlike sequential algorithms that run a search process on a single processor, parallel algorithms guide the search by a cooperative multi-processor (or thread) mechanism that offers versatile, robust and powerful tools to address large and complex VRPs (Crainic, 2008). For a survey of parallel solution methods for the VRP, the reader is referred to the books of Crainic (2008).

Simulated Annealing (SA) is a strong, robust, and versatile metaheuristic, which is easy to develop and implement. Many combinatorial optimization problems can be solved efficiently by SA. It has been used to solve the VRP and its variants, e.g., VRP (Osman, 1993), VRPTW (Chiang & Russell, 1996), time dependent VRP (Kuo, 2010), and competitive VRPTW (Tavakkoli-Moghaddam, Gazanfari, Alinaghian, Salamatbakhsh, & Norouzi, 2011). However, an application that combines parallel processing and SA to solve a VRP is rare. Czech and Czarnas (2002) proposed a p-SA (parallel SA) to solve the VRPTW problem, and Baños, Ortega, Gil, Fernández, and de Toro (2013) proposed a p-SA to solve the multi-objective VRPTW problem. Hence, the application of p-SA to solve VRP and its variants is still an open research field.

The purpose of this study is to develop an efficient meta-heuristic to solve the VRPSPDTW problem using a p-SA algorithm. The proposed p-SA is simple, versatile, and robust. The remainder of this paper is organized as follows. Section 2 presents a literature review on the VRPSPDTW, VRPSPD, and VRPTW. Section 3 formally defines the VRPSPDTW to be considered, and develops a mathematical model. Section 4 gives a detailed description of how the proposed p-SA algorithm is implemented to address the VRPSPDTW problem. Section 5 compares the performance of the p-SA with solutions reported in the literature for a variety of benchmarking instances and proposes a new benchmark for large VRPSPDTW problems. Finally, conclusions are drawn in Section 6.

2. Literature review

As stated before, three main bodies of vehicle routing literature are relevant to our problem. The first is the vehicle routing problem with simultaneous pickup–delivery and time windows. The second and third literature areas are special cases of this basic situation, i.e., the vehicle routing problem with simultaneous pickup and delivery and vehicle routing problem with time windows. The technical literature on the VRPSPDTW problem is relatively sparse compared to the body of literature accumulated for the VRPSPD and VRPTW problems.

Angelelli and Mansini (2003) were the first and only researchers to solve the VRPSPDTW problem with an exact algorithm. They implemented a branch-and-price approach based on a set covering formulation for the master problem. A relaxation of the elementary shortest path problem with time windows and capacity constraints was used for the pricing problem. A branch-and-bound approach was applied to obtain integer solutions. They modified Solomon's 100 customers instances and assumed the pickup amount P_i corresponding to the delivery amount D_i is computed by $P_i = (1-\alpha)D_i$ if i is even and $P_i = (1+\alpha)D_i$ if i is odd, where $0 \leqslant \alpha \leqslant 1$. Twenty-nine 20 customers instances were generated. The authors reported an average CPU time for these 29 instances of 26.58 s and 10.51 s for parameter α values of 0.2 and 0.8 respectively.

Several heuristics algorithms has been proposed to solve the VRPSPDTW problem. Lai and Cao (2010) proposed an Improved Differential Evolution (IDE) algorithm for solving this problem and did numerical experiments with their own instances. Boubahri, Addouche, and El Mhamedi (2011) constructed a multi-agent colonies algorithm for the problem, but did not test the algorithm. Wang and Chen (2012) proposed a co-evolution genetic algorithm with variants of the cheapest insertion method for VRPSPDTW. They also developed 65 instances adapted from the well-known Solomon benchmark (Solomon, 1987) for VRPTW. Liu et al. (2013) proposed a GA and a Tabu Search (TS) method to solve a practical vehicle scheduling problem encountered in home health care logistics.

The VRPSPD problem is better studied than the more specific class of problems noted above. VRPSPD was proposed by Min (1989) for a real life application which involved 22 customers and two vehicles to solve the book distribution problem facing a public library system. The solution was obtained by clustering customers into two disjoint groups and solving the traveling salesperson problem (TSP) for each group. Then, there was a gap of more than 10 years with limited work on this problem (Montane & Galvao, 2006). Recently, a number of researchers have revisited the problem owing to the growing interest in reverse logistics and the increasing focus on environmental protection.

For the vehicle routing problem, having only 15 customers can result in more than 10^{12} feasible solutions (Phannikul & Sindhuchao, 2010), due to the fact that the number of feasible solutions grows factorially with the number of customers. Therefore, very few exact approaches have been explored for this problem, such as: branch-and-price technique with one-commodity flow formulation (Dell'Amico, Righini, & Salani, 2006), branch-and-cut approach (Rieck & Zimmermann, 2009), branch-and-cut over one-commodity and two-commodity flow formulations (Subramanian, Uchoa, & Ochi, 2010), branch-and-cut with lazy separation (Subramanian, Uchoa, Pessoa, & Ochi, 2011) and branch-cut-and-price algorithm (Subramanian, Uchoa, Pessoa, &