Transportation Research Part B 82 (2015) 20–35

Contents lists available at ScienceDirect

Transportation Research Part B

journal homepage: www.elsevier.com/locate/trb

An evolutionary local search for the capacitated vehicle routing problem minimizing fuel consumption under three-dimensional loading constraints

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ARTICLE INFO

Article history:
Received 25 May 2015
Revised 15 August 2015
Accepted 1 October 2015
Available online 11 November 2015

Keywords:
Routing
Loading
Evolutionary local search
3L-CVRP
3L-FCVRP

ABSTRACT

This study introduces a new practical variant of the combined routing and loading problem called the capacitated vehicle routing problem minimizing fuel consumption under three-dimensional loading constraints (3L-FCVRP). It presents a meta-heuristic algorithm for solving the problem. The aim is to design routes for a fleet of homogeneous vehicles that will serve all customers, whose demands are formed by a set of three-dimensional, rectangular, weighted items. Unlike the well-studied capacitated vehicle routing problem with 3D loading constraints (3L-CVRP), the objective of the 3L-FCVRP is to minimize total fuel consumption rather than travel distance. The fuel consumption rate is assumed to be proportionate to the total weight of the vehicle. A route is feasible only if a feasible loading plan to load the demanded items into the vehicle exists and the loading plan must satisfy a set of practical constraints.

To solve this problem, the evolutionary local search (ELS) framework incorporating the recombination method is used to explore the solution space, and a new heuristic based on open space is used to examine the feasibility of the solutions. In addition, two special data structures, Trie and Fibonacci heap, are adopted to speed up the procedure. To verify the effectiveness of our approach, we first test the ELS on the 3L-CVRP, which can be seen as a special case of the 3L-FCVRP. The results demonstrate that on average ELS outperforms all of the existing approaches and improves the best-known solutions for most instances. Then, we generate data for 3L-FCVRP and report the detailed results of the ELS for future comparisons.

1. Introduction

Recently, many Chinese cities were shrouded for several days in thick fog and haze, and the Chinese government is beginning to recognize the need to reduce emissions and improve air quality. Freight transportation is essential for economic development, but it is also harmful to the environment, as a significant portion of freight transportation is carried out by trucks run on diesel engines, which are the major source of carbon dioxide (CO_2) emissions. Thus, reducing fuel consumption can directly reduce

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http://dx.doi.org/10.1016/j.trb.2015.10.001
0191-2615/

carbon emissions. In addition, fuel consumption accounts for as much as 60% of the operating cost of a vehicle, according to a study by Sahin et al. (2009). Therefore, reducing fuel consumption can also reduce operating costs.

Motivated by these facts, we study a new variant of the combined routing and loading problem, which we call the capacitated vehicle routing problem minimizing fuel consumption under three-dimensional loading constraints (3L-FCVRP). This problem is more practical than the classic vehicle routing problems (VRP). For companies, the operating cost is usually measured by the cost of consumed fuel rather the total travel distance, as fuel consumption of a vehicle is the product of the fuel consumption rate and the travel distance. The fuel consumption rate varies with the current weight of the vehicle, as shown by Xiao et al. (2012). Second, the routing plan is meaningful only if all of the goods can be loaded into the vehicle given a series of practical constraints. Thus, it is necessary to consider routing and loading simultaneously. Moreover, methodologically, the combined routing and loading problem requires to balance the efforts of exploring the solution space and identifying the loading plans. A method that simply combines the sophisticated VRP and packing algorithms may not obtain a good result within a reasonable computational time.

To solve this problem, an evolutionary local search (ELS) is used to intensively search the solution space. In addition, a multi-level diversification strategy is incorporated to diversify the search trajectory. The block exchange method exhaustively searches the neighbor regions of the current solution, and the recombination helps the search jump to other promising regions. These strategies are vital for solving this highly constrained problem successfully. The route pool helps to fully exploit the historical solution information by storing promising routes and constructing new promising solutions that are used to adjust the search trajectory. To ensure that the solution is loading-feasible, the loading check procedure is invoked for each temporal solution. Thus, our search only moves within the feasible solution space. Although the basic moves and accelerating strategies are borrowed from the work of Wei et al. (2014), we make the following contributions. First, a new practical variant of VRP is introduced. Second, a totally different search framework, ELS, is used to guide the search. The ELS is easier to implement than the adaptive variable neighborhood search (Wei et al., 2014) and obtains better results, as illustrated by our experiments. Third, a new packing heuristic based on the open space (Section 5.1) is developed to efficiently find the loading plans. Finally, most of the best-known results of 3L-CVRP instances are updated. More precisely, two special data structures, Trie and Fibonacci heap, are adopted to speed up the procedure. The Trie structure not only helps avoid duplicate loading checks of the same routes, but also makes it available to spend increasing effort on the frequently encountered routes. These routes are usually promising to be in the final best solution. The Fibonacci heap helps to avoid duplicating objective calculations of moves, and only invoke the loading check procedure for parts of promising moves.

The remainder of this paper is organized as follows. Section 2 gives an overview of the relevant literature. Section 3 provides the detailed description of 3L-FCVRP. The entire ELS search framework and ingredient functions are presented in Section 4. Section 5 describes the local search procedure for the loading component. The extensive results for the 3L-CVRP and 3L-FCVRP are reported in Section 6. Finally, Section 7 concludes the paper.

2. Literature review

The original combined routing and loading problem, the capacitated vehicle routing problem with two-dimensional loading constraints (2L-CVRP), was proposed by Iori et al. (2007). It aims at minimizing the total distance traveled by all of the vehicles and assumes that products cannot be stacked on top of each other. Based on the 2L-CVRP, Leung et al. (2013) proposed the heterogeneous fleet vehicle routing problems with two-dimensional loading constraints (2L-HFVRP). Recently, Khebbache-Hadji et al. (2013) introduced the time window into the 2L-CVRP and proposed the two-dimensional loading capacitated vehicle routing problem with time windows (2L-CVRPTW).

Gendreau et al. (2006) first proposed the capacitated vehicle routing problem with three-dimensional loading constraints (3L-CVRP), which considers many of the practical constraints on loading, such as the fragility, support, and last in first out (LIFO) constraints. The 3L-CVRP can be seen as a special case of the 3L-FCVRP by assuming that the fuel consumption rate of a vehicle is constant regardless of the weight of the vehicle. Zachariadis et al. (2012) studied the pallet-loading vehicle routing problem (PPVRP) by integrating routing with pallet-loading constraints. In this problem, the products are first stacked into pallets, which are then loaded onto the vehicles. Recently, Zachariadis et al. (2013) proposed a very complex problem called the pick-up and delivery routing problem with time windows and pallet loading (PDRP-TWP). Surveys of routing problems with 2D and 3D loading constraints are provided by Wang et al. (2009), Iori and Martello (2010) and Iori and Martello (2013). We refer the reader to the papers by Bektaş and Laporte (2011); Franceschetti et al. (2013); Santos et al. (2010); Zachariadis et al. (2015) for more variants of the routing problems.

These vehicle routing problems with loading constraints combine two NP-hard problems, thus an exact approach can only be used to solve small instances. The only exact approach was proposed by Iori et al. (2007) for 2L-CVRP, which can solve instances with up to 35 customers in 24 h. Most previous studies used a meta-heuristic to solve the routing sub-problem. These approaches include tabu search (Bortfeldt, 2012; Doerner et al., 2007; Gendreau et al., 2006; 2008; Leung et al., 2011b; Tao and Wang, 2015; Tarantilis et al., 2009; Zachariadis et al., 2009; Zhu et al., 2012), ant colony optimization (Fuellerer et al., 2009; 2010), simulated annealing (Leung et al., 2013; 2010), honey bee mating optimization (Ruan et al., 2013), multi-start evolutionary local search (Duhamel et al., 2011), and variable neighborhood search (Wei et al., 2014; 2015). To the best of our knowledge, the variable neighborhood search frameworks proposed by Wei et al. (2015) and Wei et al. (2014) are the state-of-the-art methods for the 2L-CVRP and 3L-CVRP, respectively.