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Discrete Optimization

Integrated distribution and loading planning via a compact metaheuristic algorithm

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ABSTRACT

The present article examines a vehicle routing problem integrated with two-dimensional loading constraints, called 2L-CVRP. The problem is aimed at generating the optimal route set for satisfying customer demand. In addition, feasible loading arrangements have to be determined for the transported products. To solve 2L-CVRP, we propose a metaheuristic solution approach. The basic advantage of our approach lies at its compact structure, as in total, only two parameters affect the algorithmic performance. To optimize the routing aspects, we propose a local-search method equipped with an effective diversification component based on the regional aspiration criteria. The problem's loading requirements are tackled by employing a two-dimensional packing heuristic which repetitively attempts to develop feasible loading patterns. These attempts are effectively coordinated via an innovative, simple-structured memory mechanism. The overall solution framework makes use of several memory components for drastically reducing the computational effort required. The performance of our metaheuristic development has been successfully evaluated on benchmark instances considering two distinct versions of the loading constraints. More specifically, the algorithm managed to improve or match the majority of best known solution scores for both problem versions.

1. Introduction

The distribution of goods constitutes one of the most important operations in the modern business environment, with numerous everyday applications. For this reason, researchers and practitioners have been devoted to both modeling and optimizing such transportation logistics activities. The most widely known and studied distribution model is the vehicle routing problem (VRP) which examines the distribution of products from a central location to a set of geographically dispersed customers with the use of a homogeneous vehicle fleet. This classical VRP version can be regarded as an idealized model of the routing problems met in practice, obtained after making simplifying assumptions on various practical elements of real-life distribution systems. The increase of computational power provided by modern computer systems together with methodological advances allow researchers to investigate more realistic distribution models which incorporate complex operational characteristics which in the past were thought to be too hard to tackle. Following this research stream, composite routing and packing problems have been recently modeled and introduced in the literature. The central characteristic of these problems is that apart from optimizing the vehicle routing operations, the physical dimensions of transported goods are taken into account, so that feasible loading arrangements of goods must be identified. In other words, these integrated models promote a more accurate and effective decision making compared to traditional vehicle routing approaches which employ oversimplifying one-dimensional volume and weight capacity constraints, even when solid products of different shapes and sizes are transported.

The present article studies and solves the first composite routing-packing problem that appeared in the vehicle routing literature, called the Capacitated Vehicle Routing Problem with Two-Dimensional Loading constraints (2L-CVRP). The 2L-CVRP model was originally introduced by Iori et al. (2007). It considers that a homogeneous vehicle fleet based in a central depot must be routed to deliver requested products to a set of customer locations. The products to be transported are thought to be rectangular and non-stackable items. The 2L-CVRP model is aimed at determining the optimal routes for executing the necessary delivery operations, as in the case of the well-known classical Capacitated Vehicle Routing Problem (Laporte, 2009). Moreover, for each of the generated routes, the problem calls for the determination of a feasible two-dimensional orthogonal loading arrangement of the transported items onto the vehicle loading surface. This loading requirement is closely related to the two-dimensional bin packing problem (2BPP) which involves the minimization of the number of identical rectangular bins required for packing a predetermined set of rectangular items.

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In terms of 2L-CVRP solution methodologies, Iori et al. (2007) propose an exact branch-and-cut algorithm for the routing aspects, whereas the loading requirements of the problem are tackled via a branch-and-bound approach. The algorithm is capable of optimally solving 2L-CVRP instances of up to 25 customers and 91 items within 24 hours of computational time. To deal with larger-scale instances, Gendreau et al. (2008) propose a metaheuristic solution approach that employs tabu search for optimizing the routing characteristics, whereas feasible loading patterns are identified via a heuristic procedure based on the Touching Perimeter rule (Lodi et al., 1999). Zachariadis et al. (2009) describe a hybridization of tabu-search and guided local search which operates in parallel with a collection of heuristics for developing feasible item loadings. The work of Fuellerer et al. (2009) describes an Ant Colony Optimization approach combined with several two-dimensional packing heuristics in pursuit of feasible loading patterns. Another algorithmic design has been proposed by Leung et al. (2011). Their algorithm deals with the routing aspects via a hybridization of tabu search and extended guided local search, whereas loading feasibility of routes is investigated by a set of two dimensional packing heuristics. The most recent paper on the 2L-CVRP model is due to Duhamel et al. (2011). The authors propose a hybrid algorithm which combines the powers of the greedy randomized adaptive search (GRASP) and evolutionary local search (ELS) strategies. The loading aspects are dealt with by firstly relaxing the corresponding two-dimensional bin packing problems into simpler resource constrained project scheduling (RCPSP) ones. The generated routes are then modified in order to satisfy the original 2L-CVRP loading requirements. A vehicle routing problem with similar two dimensional loading constraints has been introduced by Malapert et al. (2008), examining the pick-up and delivery extension of the basic 2L-CVRP model.

Regarding vehicle routing problems integrated with loading constraints, Gendreau et al. (2006) have generalized 2L-CVRP by imposing three-dimensional loading constraints for the transportation of rectangular and stackable boxes. The problem is referred to as the capacitated vehicle routing problem with three-dimensional loading constraints (3L-CVRP). The authors solve the examined problem via a tabu search metaheuristic development. Further solution approaches for the 3L-CVRP model have been published by Tarantilis et al. (2009), Fuellerer et al. (2010), Ruan et al. (2011), Zhu et al. (2012) and Bortfeldt (2012). Another routing problem with three-dimensional packing requirements which imposes time-window constraints has been studied by Moura and Oliveira (2009). Zachariadis et al. (2012) examine an integrated routing-packing model of great practical importance, called the pallet packing vehicle routing problem. As its name suggests, the examined model considers that transported boxes must be feasibly packed into pallets which are then loaded onto the vehicles. A routing application with loading constraints faced by an Austrian wood product retailer is discussed in the studies of Doerner et al. (2007b) and Tricoire et al. (2011). The interested reader is referred to the work of Iori and Martello (2010) which reviews published vehicle routing problems integrated with loading constraints.

The purpose of the present article is to propose an innovative and effective solution approach for the 2L-CVRP. In terms of the routing aspects, we propose a local-search optimization approach, coordinated via a single-parameter policy which adapts to the progress of the conducted search. Regarding the loading constraints, they are tackled via a packing heuristic which attempts to identify feasible packing arrangements for the transported goods. The packing heuristic behavior is controlled by an innovative memory mechanism which is aimed at generating diverse packing structures in order to maximize the probability of obtaining feasible loading arrangements. Finally, various memory components are used to reduce the computational effort dedicated for examining loading feasibility.

The basic advantage of the overall solution framework lies at its compact and simple structure. Contrary to previously published complex 2L-CVRP approaches, our algorithm makes use of two search parameters in total, one for the routing and one for the loading aspects. This feature is very important, as it promotes a robust performance and eliminates the time required for tuning experiments, when problems of diverse characteristics are solved. The proposed solution approach was tested on 2L-CVRP benchmark problems. It produced fine quality results, improving several best known solutions.

The remainder of the present article is organized as follows: Section 2 describes the 2L-CVRP model in detail. In Section 3, we present the routing optimization component of the proposed methodology, whereas the heuristic procedure for investigating the loading constraints is discussed in Section 4. Finally, Section 5 provides and evaluates the obtained computational results, followed by Section 6 which concludes the paper.

2. Description of the 2L-CVRP model

The 2L-CVRP model is defined on a complete graph $G = (V,A)$, where $V = \{0, 1, \ldots, n\}$ is the vertex set and A is the arc set. Vertex 0 represents the depot where a fleet of k vehicles is available. Each vehicle has a maximum carrying load of weight Q and carries a loading surface with length and width equal to L and W, respectively. With each arc $(i,j) \in A$ is associated a known and non-negative travel cost c_{ij} reflecting the distance, the travel-time or the actual monetary cost required for traveling between vertices i and j. Let N denote the set of customer vertices ($N = V\setminus\{0\}$). Each customer $i \in N$ is considered to demand a set of items $T_i = \{0, \ldots, m_i\}$ of total weight equal to q_i. The length and width dimensions of an item $j \in T_i$ are denoted by l_{ij} and w_{ij}, respectively.

The goal of the 2L-CVRP is to identify the set of routes which minimize the total required travel cost. The produced routes are subject to the following constraints:

- Each route starts and terminates from and to the central depot, respectively.
- Each customer vertex is visited once by exactly one route.
- The total weight of the items required by the customer subset assigned to each route does not exceed the vehicle capacity Q.
- All items demanded by the customers visited by a route are transported by the vehicle implementing this route.
- For each vehicle, there exists a feasible, two-dimensional, orthogonal packing of the transported items onto the loading surface (loading constraints).

An example solution of a 2L-CVRP instance that involves 5 customers, 12 items and 2 vehicles is depicted in Fig. 1.

The loading constraints of the 2L-CVRP guarantee that all items demanded by the customers visited by a single route can be orthogonally packed into the loading surface of the corresponding vehicle. Obviously, loaded items must not overlap, nor exceed the vehicle surface boundaries. In practical cases, additional loading constraints can be imposed to ensure that unloading operations are efficiently performed. This is discussed by Iori et al. (2007) who introduce the *sequence* (often referred to as LIFO) constraint which ensures that whenever a customer i is visited, all T_i items can be unloaded by employing a sequence of straight movements (one per item) parallel to the length dimension of the vehicle surface. In other words, no item of customer j to be served later than customer i can be placed between items of i and the loading/unloading door of the vehicle. Moreover, depending on the