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Heuristic algorithms for a three-dimensional loading capacitated vehicle routing problem in a carrier ☆

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ABSTRACT

In this paper, we present heuristic algorithms for a three-dimensional loading capacitated vehicle routing problem arising in a real-world situation. In this problem, customers make requests of goods, which are packed in a sortment of boxes. The objective is to find minimum cost delivery routes for a set of identical vehicles that, departing from a depot, visit all customers only once and return to the depot. Apart of the usual 3D container loading constraints which ensure that the boxes are packed completely inside the vehicles and that the boxes do not overlap each other in each vehicle, the problem also takes into account constraints related to the vertical stability of the cargo and multi-drop situations. The algorithms are based on the combination of classical heuristics from both vehicle routing and container loading literatures, as well as two metaheuristic strategies, and their use in more elaborate procedures. Although these approaches cannot assure optimal solutions for the respective problems, they are relatively simple, fast enough to solve real instances, flexible enough to include other practical considerations, and normally assure relatively good solutions in acceptable computational times in practice. The approaches are also sufficiently generic to be embedded with algorithms other than those considered in this study, as well as they can be easily adapted to consider other practical constraints, such as the load bearing strength of the boxes, time windows and pickups and deliveries. Computational tests were performed with these methods considering instances based on the vehicle routing literature and actual customers' orders, as well as instances based on a real-world situation of a Brazilian carrier. The results show that the heuristics are able to produce relatively good solutions for real instances with hundreds of customers and thousands of boxes.

1. Introduction

The *three-dimensional loading capacitated vehicle routing problem* (3L-CVRP) is the result of the combination of the capacitated vehicle routing problem (CVRP) with the container loading problem (CLP). In this combined problem, generically, the challenge is to optimize simultaneously the planning of the vehicles' routes and the cargo arrangement inside the vehicle, while addressing a series of practical considerations inherited from both vehicle routing (Golden, Raghavan, & Wasil, 2008; Laporte, 2009; Toth & Vigo, 2002) and container loading (Bischoff & Ratcliff, 1995; Bortfeldt & Wäscher, 2013; Wäscher, Haussner, & Schumann, 2007) literatures.

This effort arises from the attempt to avoid expressing the demands of the customers simply as their weights or volumes. In other words, if the demand constraints are seen from a one-dimensional point of view, it is assumed that each demand fills a certain section of the vehicle or that the cargo shapes up smoothly according to the vehicle shape. However, when the demands are put in terms of rigid discrete items, such as boxes, their geometry may lead to losses of space or even to infeasible solutions if the vehicle has not enough capacity. If other practical constraints are also considered, the coupling of the routing and loading structures becomes even more complex.

The 3L-CVRP considers a fleet of identical vehicles that must run minimum cost routes to deliver boxes to a set of customers, departing from and returning to a depot. Besides the non-overlap of the three-dimensional boxes, the constraints that have been usually considered are the vertical stability of the cargo and the multi-drop situations (also known as LIFO constraints), although other constraints may also appear, such as the load bearing

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strength of the boxes, time windows and pickups and deliveries. The approaches used to solve the problem have been mainly heuristic (Bortfeldt, 2012; Bortfeldt & Homberger, 2013; Ceschia, Schaerf, & Stützle 2013; Fuellerer, Doerner, Hartl, & Iori, 2010; Gendreau, Iori, Laporte, & Martello, 2006; Lacomme, Toussaint, & Duhamel, 2013; Moura & Oliveira, 2009; Ruan, Zhang, Miao, & Shen, 2013; Tao & Wang, 2013; Tarantilis, Zachariadis, & Kiranoudis, 2009; Zachariadis, Tarantilis, & Kiranoudis, 2012, 2013; Zhu, Qin, Lim, & Wang, 2012). The integrated problem is usually hierarchically decomposed, where the vehicle routing is solved at the higher level and the container loading at the lower level. Recent reviews on the emerging literature on these problems are presented in Iori and Martello (2010, 2013). Table 1 presents a compilation of the published papers that addressed some integration of vehicle routing and three-dimensional loading problems, focusing on the main features considered, which are abbreviated as follows:

C1 – Orientation constraints	C6 – Weight limit constraints
C2 – Cargo stability constraints	C7 – Time windows constraints
C3 – Multi-drop constraints	C8 – Time-constrained routes
C4 – Load bearing/fragility constrains	C9 – Pickup and delivery points
C5 – Boxes in pallets first, pallets in vehicles second	C10 – Split deliveries

In this paper, we present reasonably simple and effective heuristic algorithms for an integrated vehicle routing and three-dimensional loading problem arising in the context of a carrier. Apart of the geometrical constraints, that ensure that the boxes are packed completely inside the vehicles and that the boxes do not overlap each other in each vehicle, the vertical stability of the cargo (C2) and the multi-drop situations (C3) are also taken into account. Cargo stability (e.g., Fanslau & Bortfeldt, 2010; Gonçalves & Resende, 2012; Junqueira, Morabito, & Yamashita, 2012a; Zheng, Chien, & Gen, 2014; Zhu & Lim, 2012) refers to the support of the bottom faces of the boxes, in the case of vertical stability (i.e., the boxes must have their bottom faces supported by the top faces of other boxes or by the floor of the container), and to the support of the lateral faces of the boxes, in the case of horizontal stability. Multi-drop situations (e.g., Ceschia & Schaerf, 2013; Christensen & Rousøe, 2009; Junqueira, Morabito, & Yamashita, 2012b; Lai, Xue, & Xu, 1998) refer to cases where boxes that are delivered to the same customer (destination) must be placed close to each other in the vehicle, and the loading pattern must take into account the delivery route of the vehicle and the sequence in which the boxes are unloaded. The practical importance of incorporating these constraints to the problem is to avoid loading patterns where boxes are floating inside the vehicles or where an unnecessary additional handling is incurred when each drop-off point of the route is reached, which will become more evident by the real-world situation described in Section 2. It is also assumed that the boxes and the container/vehicle are of rectangular shape.

To our knowledge, the specialized literature has been concentrated in presenting solution methods that are able to deal with 3L-CVRP instances (Gendreau et al., 2006) with dozens of customers and dozens of boxes of relatively *many types* (i.e., strongly heterogeneous instances), which configures the integration of the CVRP with the 3D-R-SBSBPP (*three-dimensional rectangular single bin size bin packing problem*) or with the 3D-R-SKP (*three-dimensional rectangular single knapsack problem*), according to the typology presented in Wäscher et al. (2007), and which is a common scenario in courier services or when retailers need to perform deliveries of purchases in small quantities to final customers. In this paper, motivated by visits performed on a Brazilian carrier, we present solution methods that are able to deal with 3L-CVRP instances with hundreds of customers and thousands of boxes of relatively *few types* (i.e., weakly heterogeneous instances), which configures the integration of the CVRP with the 3D-R-SSSCSP (*three-dimensional rectangular single stock size cutting stock problem*) or with the 3D-R-SLOPP (*three-dimensional rectangular single large object placement problem*), according to the typology presented in Wäscher et al. (2007), and which is a common scenario in carrier services or when companies need to perform deliveries of batches of goods to warehouses or to retailers, or from warehouses to retailers. The sortment of boxes plays an important role in the design of packing heuristics, whereas packing algorithms designed for dealing with strongly heterogeneous sortments of boxes may not be suitable for dealing with weakly heterogeneous sortments of boxes, and vice versa. The proposed solution approaches take into account this gap, besides being relatively simple, fast enough to solve real instances, flexible enough to include other practical considerations, and normally assuring relatively good solutions in acceptable computational times in practice, still being sufficiently generic to be embedded with algorithms other than those considered in this study.

This work is organized as follows. In Section 2, we describe the 3L-CVRP arising in the context of a carrier. In Section 3, we review classical heuristics from both vehicle routing and container loading literatures, as well as two metaheuristic algorithms. In Section 4, we build on the heuristics presented in Section 3, extending and adapting them to address the 3L-CVRP, and we incorporate them in more elaborate procedures. In Section 5, we analyze the results

Table 1
Overview of constraints addressed in publications on integrated vehicle routing and three-dimensional loading problems.

References in alphabetical order	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
Bortfeldt (2012)	x	x	x	x		x				
Bortfeldt and Homberger (2013)	x	x	x				x			
Ceschia et al. (2013)	x	x	x	x		x				x
Fuellerer et al. (2010)	x	x	x	x		x				
Gendreau et al. (2006)	x	x	x	x		x				
Junqueira, Oliveira, Carravilla, and Morabito (2013)	x	x	x	x						
Lacomme et al. (2013)	x					x				
Moura and Oliveira (2009)	x	x	x				x			
Ruan et al. (2013)	x	x	x	x		x				
Tao and Wang (2013)	x	x	x	x		x				
Tarantilis et al. (2009)	x	x	x	x		x				
Zachariadis et al. (2012)	x	x			x		x	x		
Zachariadis et al. (2013)	x	x			x		x		x	
Zhu et al. (2012)	x	x	x	x		x				