Transportation Research Part B 91 (2016) 565–581

Contents lists available at ScienceDirect

Transportation Research Part B

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

A container loading algorithm with static mechanical equilibrium stability constraints

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ARTICLE INFO

Keywords:
Container loading problem
Static stability
Maximal-spaces
Genetic algorithms

ABSTRACT

The Container Loading Problem (CLP) literature has traditionally guaranteed cargo static stability by imposing the full support constraint for the base of the box. Used as a proxy for real-world static stability, this constraint excessively restricts the container space utilization and has conditioned the algorithms developed for this problem. In this paper we propose a container loading algorithm with static stability constraints based on the static mechanical equilibrium conditions applied to rigid bodies, which derive from Newton's laws of motion. The algorithm is a multi-population biased random-key genetic algorithm, with a new placement procedure that uses the *maximal-spaces* representation to manage empty spaces, and a layer building strategy to fill the *maximal-spaces*. The new static stability criterion is embedded in the placement procedure and in the evaluation function of the algorithm. The new algorithm is extensively tested on well-known literature benchmark instances using three variants: no stability constraint, the classical full base support constraint and with the new static stability constraint—a comparison is then made with the state-of-the-art algorithms for the CLP. The computational experiments show that by using the new stability criterion it is always possible to achieve a higher percentage of space utilization than with the classical full base support constraint, for all classes of problems, while still guaranteeing static stability. Moreover, for highly heterogeneous cargo the new algorithm with full base support constraint outperforms the other literature approaches, improving the best solutions known for these classes of problems.

1. Introduction

The Container Loading Problem (CLP) is a real-world driven, combinatorial optimization problem that addresses the optimization of the spatial arrangement of cargo inside containers or transportation vehicles, maximizing the usage of space.

As an assignment problem, it can have two basic objectives: the maximization of the value of the cargo loaded, when the number of containers is not sufficient to accommodate all the cargo, or the minimization of the value of containers, when there are sufficient containers to accommodate all the cargo.

The problem belongs to the wider combinatorial optimization class of Cutting and Packing problems. According to the typology defined by Wäscher et al. (2007) for Cutting and Packing problems, these can be classified according to

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http://dx.doi.org/10.1016/j.trb.2016.06.003
0191-2615/

dimensionality, assortment of large items, assortment of small items, kind of assignment and shape of small items. In this paper we will consider two types of problem with an output maximization objective. These problems can be classified either as three-dimensional, rectangular single large object placement problems (3D-SLOPP) or as three-dimensional, rectangular single knapsack problems (3D-SKP), depending on the cargo heterogeneity.

The CLP is highly relevant to the field of transport management. The effect of globalization led to a world where products and services are exchanged in increasing numbers and distances by and to an increasing number of origins and destinations, and where containerization is the standard method of transporting goods and cargo worldwide. This scenario places a number of challenges to achieve an efficient transport system, required for maintaining prosperity and economic development. New problems that arose such as the ones related with the urban freight transportation (Sánchez-Díaz et al., 2015) or the designs of intermodal networks (Meng and Wang, 2011) can directly benefit from a reduction of the congestion of cargo transport units that an efficient container space usage can provide.

The arrangements for loading cargo into containers should comply with various requirements: cargo should not become damaged during transportation, transportation space should be used efficiently and workers' safety should not be breached during loading and unloading of cargo.

However, if the approach to the problem does not consider real-world constraints, such as cargo stability, container weight-limit or cargo orientation constraints, the solution will be of limited applicability to real-world scenarios. Cargo stability is considered in the literature as one of the most important CLP constraints. Its impact is not confined to the cargo as it can also influence the safety of both workers involved in loading operations and other persons or vehicles during transportation.

In the CLP literature, cargo stability is sometimes addressed separating static and dynamic stability. Cargo static stability has been guaranteed by imposing the full support constraint on the base of the boxes. Although guaranteeing static stability, it excessively restricts the container space usage and does not necessarily meet real-world needs when e.g., overhanging cargo is allowed. The rather oversimplified way static stability has been treated by the majority of the authors it is also present in existing approaches to dynamic stability, where stability is measured by the mean number of boxes supporting the items excluding those placed directly on the floor and the percentage of boxes with insufficient lateral support (Ramos et al., 2015).

The CLP addressed in this work can be stated as follows: A given set of small items of parallelepiped shape of type $k (k = 1, \ldots, K)$ (known as boxes), $B = b_1, b_2, \ldots, b_K$, where each box type, in quantity n_k, is characterized by its depth, width and height (d_k, w_k, h_k) are to be loaded into a large object of parallelepiped shape (known as a container), C, characterized by its depth, width and height, (D, W, H), with the objective of achieving a maximum utilization of the volume of the container, while meeting the following geometric loading constraints:

- Each face of a box must be parallel to one of the faces of the container;
- There must be no overlap between the boxes;
- All boxes must lie entirely within the container;
- Each box must be placed according to one of its possible orientations—each box type can have up to six possible orientations.

The mechanical properties of the container and the boxes also necessitate the following additional practical constraints:

- boxes can only be loaded through the container entrance;
- static stability—each box must be able to maintain its loading position undisturbed during cargo loading;
- all boxes are rigid;
- the centre of gravity of each box is assumed to be its geometric centre.

The dimensions (D, W, H) of container C lie parallel to the x, y and z axes, respectively, of the first octant of a Cartesian coordinates system, with the back-bottom-left corner lying at the origin of the coordinates system. The placement of a box b_i in the container is given by its minimum and maximum coordinates, (x_{1i}, y_{1i}, z_{1i}) and (x_{2i}, y_{2i}, z_{2i}), respectively.

The aim of this work is to present an algorithm for the CLP that addresses cargo stability under a realistic framework. The proposed algorithm combines a multi-population biased random-key genetic algorithm with a constructive heuristic that enforces a static stability constraint based on the static mechanical equilibrium conditions applied to rigid bodies, which derive from Newton's laws of motion. The constructive heuristic uses a *maximal-spaces* representation to manage empty spaces, and a layer approach for filling the *maximal-spaces*.

The remainder of the paper is organized as follows. Section 2 presents an overview of the literature covering the CLP and static stability within the CLP. In Section 3 the Container Loading Algorithm with Static Stability is presented. Section 4 reports the results from the computational experiments. Finally, Section 5 draws some conclusions from the findings.

2. Literature review

Many approaches have been proposed for solving the 3D-SLOPP and the 3D-SKP. The number of exact methods proposed is very limited and these can only solve problems of limited size. Exact methods were developed by Padberg (2000), Fekete et al. (2007), Junqueira et al. (2012b) and Junqueira et al. (2012a). Alternatively, other methods have been proposed to find near-optimal packing solutions. Fanslau and Bortfeldt (2010) classified these methods as conventional heuristics,