Solving the 3-D Yard Allocation Problem for Break Bulk Cargo via Variable Neighborhood Search Branching

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1 Introduction

While the number of publications and researches in the field of container handling has increased considerably in the last three decades ([3]), the literature about port yard optimization and vehicle-packing problems reveals a lack of mathematical modeling and analysis concerning break bulk load, despite the huge impact of this class of cargo on transportation and international trade. Indeed, regardless of several political and economic factors that occurred in the last few years, maritime transportation has continued growing, pushed by the increasing request of dry cargo (+5.7% according to UNCTAD 2013).

The optimal disposition of brake bulk cargo in a port yard shares some futures with the 3-D Bin Packing Problem (3-D BPP). Due to its NP-hardness, heuristic approaches and orientation constraints relaxation are commonly found throughout the literature of the 3-D BPP to the aim of decreasing the required computational time ([7]). The first exhaustive model to solve a 3-D BPP that allowed orthogonal rotations was proposed by [6] but it could only solve instances with few items. The model was re-elaborated by [11] to suit a single bin loading problem with a variable height that has to be minimized by the objective function to obtain a dense packing. Concerning real world packing problems, [4] proposed one of the first heuristics for pallet loading taking into account different item sizes and stability issues. A review that groups and characterizes the various constraints used in container loading problems is given by [3]. An approach for a vertical stability constraint was proposed by [5] and an analysis for an orientation constraint allowing rotation only in the horizontal plane is found in the study of [9].

Considering the enormous lack of literature regarding break bulk ports, [10] can be considered the first to study optimization problems of berth allocation and yard assignment, highlighting principally the differences and the elements to take into account in this context. The objective of the model developed is the minimization of the total service time of vessels berthing at the port through an exact solution algorithm based on a branch and price framework to solve the integrated problem. Among the few researches in this field, moved by systematic and analytic approach through the use of mathematical modeling, the work conducted by [8] succeeded in finding optimal dispositions of break bulk cargo, like granite blocks in a port yard, considering 3-D disposition of the cargo and the handling time to move the cargo to/from vessels that are moored in specific berthing positions. They present a Mixed Integer Linear Programming (MILP) formulation. However, exact solutions are obtained only for small scale problems due to the strong NP-hardness of the problem, requiring a metaheuristic approach to fit real scale sized instances.

For this reason in this paper we develop a matheuristic based on the MILP formulation introduced by [8]. The matheuristic implemented is a Variable Neighborhood Search Branching (VNSB), method introduced by [2].

The rest of the paper is organized as follows: Section 2 describes the 3-D Yard Allocation Problem for Break Bulk Cargo (3-D YAP4BBC); Section 3 proposes a VNSB for the 3-D YAP4BBC. Finally, Section 4 shows some numerical results carried out on benchmark instances and in Section 5 we draw some conclusions.

2 Problem description

As shown in Figure 1, a port yard can be schematized as a rectangle with its length assumed parallel to the coast line and consequently to the quay; the coordinates are defined by a reference system that originates in the front bottom right corner of the yard. The X axis is taken parallel to the quay with the increasing positive values pointing toward the yard area, the Y axis is taken perpendicular to the coast line and parallel to the yard width with the positive values pointing toward the yard. As a consequence, because of the distance between the yard and the berth, the y berthing coordinate of the ships will generally be negative and equal in value to this distance. The Z axis also originates in the front bottom right corner of the yard and is considered facing upward, defining a right handed set of coordinates with X and Y axis.

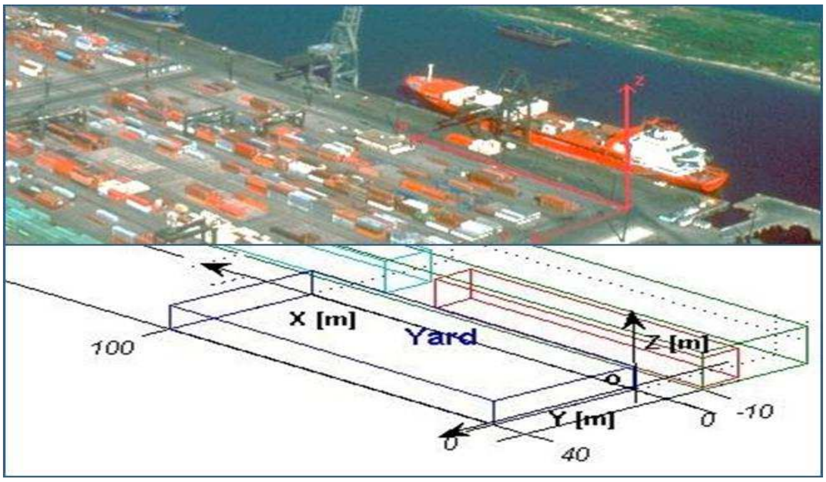

Fig. 1. Schema of a port yard

The 3-D Yard Allocation Problem for Break Bulk Cargo (3-D YAP4BBC) consists in finding the optimal disposition of the cargo (granite blocks) that minimizes the handling time to move the cargo to/from vessels that are moored in specific berthing positions without reshuffling (i.e. a successive block rearrangement) since it would heavily affect the operational time of loading and unloading. The disposition of each granite block is identified by the coordinates of the front left bottom corner of the block. The minimization of the handling time consists in the minimization of the total distance between every block and the loading spot of the vessel which it is assigned to. The distance considered is the Manhattan distance since the blocks are moved by way of a crane. The disposition of the blocks has to respect the following constraints:

(i) due to stability reason, a block must be always put with its biggest surface leaned on the ground, with the smaller of the three dimensions of its always coinciding with the height;

(ii) to avoid toppling, a block put on top of another one must be smaller or equal to the one below it in both the two base dimensions;

(iii) to respect the handling equipment limit in terms of height and to avoid the risk of toppling, the height of each pile must not exceed a given threshold (due to the maximum lifting height reachable by a crane);

(iv) to prevent reshuffling, only blocks of the same ship can be put in the same pile;

(v) to take into account the service priority of the vessels, the higher is the priority of a vessel, the closer the blocks assigned to it must be located.

[8] proposes a MILP model for the 3-D YAP4BP based on the following input parameters and decision variables:

Input parameters

- N set of blocks;
- S set of ships;
- (l_i, w_i, h_i) length, width and height of block $i \in N$;
- (L, W, H) length, width, height of the port yard;
- σ_i parameter indicating to which ship block $i \in N$ is associated to;
- $(\tilde{x}_j, \tilde{y}_j)$ loading spot coordinates of ship $j \in S$;
- Pr_j Parameter indicating priority index of ship $j \in S$.

Decision variables

- (x_i, y_i, z_i) coordinates of the front-left bottom corner of block $i \in N$
- (lx_i, ly_i, lz_i) binary variables indicating whether the length of block $i \in N$ is parallel to the X,Y or Z axis: their value is equal to 1 if there is parallelism, else to 0;
- (wx_i, wy_i, wz_i) binary variables indicating whether the width of block $i \in N$ is parallel to the X, Y or Z axis;
- (hx_i, hy_i, hz_i) binary variables indicating whether the height of block $i \in N$ is parallel to the X, Y or Z axis;
- $Dist_{ij}$ variable measuring the Manhattan distance between block $i \in N$ and the loading spot of ship σ_i;
- a_{ik}, b_{ik}, c_{ik}, d_{ik}, e_{ik}, f_{ik} binary variables to define the relative positioning of the blocks each other (e.g. a_{ik} variable is equal to 1 if block i is on the left side of block k, 0 otherwise).

3 A VNSB for the 3-D YAP4BBC

The Variable Neighborhood Search and Branching (VNSB) is a matheuristic introduced by [2] to solve any 0-1 Mixed Integer Linear Program (0-1 MILP). It consists in adding linear constraints to the original problem for a systematical change of neighborhood inside the general VNS schema. The idea of implementing a neighborhood by adding a linear constraint to the MILP model has been firstly presented in the work of [1], known as Local Branching Method. Thus, the VNSB combines the VNS approach with the Local Branching one.

Since the formulation of the 3-D YAP4BBB proposed by [8] is a special case of 0-1 MILP, it can be solved through the VNSB. We chose to impose the Local Branching constraints only on the binary variables a_{ik}, c_{ik}, e_{ik}, since they are the variables that mainly affect the complexity of the model being $O(|N|^2)$ (while the values of variables b_{ik}, d_{ik}, f_{ik}, can be univocally determined from them). With reference to the pseudo-code described in [2], we set the parameter k_{step}, aimed to control the depth of the neighborhood explored during the shaking phase, equal to 5 while the node time limit equal to 10 seconds. Beyond the classical total time limit (here fixed to 3600 seconds), the stopping criterion is also based on the maximum number of consecutive iterations without improvements (here fixed to 10 iterations).

4 Some numerical results

In this section, we describe the computational tests carried out on some benchmark instances of the 3-D YAP4BBC. The aim is to compare the performance of the MILP formulation proposed by [8] and solved by a state of the art solver (CPLEX) with the VNSB described in the previous section. Both the MILP formulation and the VNSB have been implemented in AMPL and both the MILP formulation and the MILP subproblems produced by the VNSB are solved with CPLEX 12.5 on a PC Intel Xeon 2.80 GHz with 2GB RAM.

The instances have been developed for the port yard of Vitoria (Espirito Santo, Brazil) with measures, in meters, $(L, W, H) = (100.0, 40.0, 8.0)$. The instances are organized in two sets corresponding to two scenarios, HO and HE, that differ by the kind of blocks taken into consideration: HO consists of an homogeneous set of blocks with $(l_i, w_i, h_i) = (3.5, 3.0, 2.0)$ $\forall i \in N$; HE consists of an heterogeneous set of blocks with randomly generated dimensions, $l_i, w_i \in [2.75, 3.5]$ and $h_i \in [1.0, 2.0]$, reflecting the real world dimensions of a granite block. Each set of instances, is characterized by a growing number of blocks, with $|N| = 10, 50, 70, 100, 200$, and a fixed number of ships ($|S| = 3$). The input data referring to the vessels' berthing coordinates derive from the solution of the Berth Allocation Problem ([10]) for the port of Vitoria, taking into consideration the vessels dedicated to granite blocks transportation only.

The numerical results are reported in Table 1 where the columns represent respectively the instance name, the number of blocks, the objective function value of the best feasible solution obtained by CPLEX solving the MILP formulation [8] within the CPU time limit, the percentage relative gap with the lower bound computed by CPLEX, the CPU time, the objective function value of the best feasible solution obtained by the VNSB, the percentage relative gap with the best feasible solution obtained by CPLEX, the CPU time. The numerical results, although preliminary, show that in the same CPU time limit the VNSB finds solutions better than those yielded by CPLEX, with an average improvement of 4.16% on the HO instances and of 3.84% on the HE ones. We can also observe that the relative percentage gap between the solution value of CPLEX and of VNSB tends to increase for increasing values of $|N|$. For low values of $|N|$ the VNSB is not convenient since can become more time consuming than CPLEX (see instances 10B3S-HO and 10B3S-HE), whereas for high values of $|N|$ the best feasible solution is found often far before reaching the CPU time limit (on average 1000 seconds in advance) while CPLEX always reaches the CPU time limit.

Table 1: Numerical Comparisons between CPLEX and VNSB.

Instance	$\|N\|$	CPLEX			VNSB		
		OBJ	GAP%	CPU	OBJ	GAP%	CPU
10B3S-HO	10	3575.69	0	0.54	3575.69	0	162.29
50B3S-HO	50	19512.36	8.68	3600	19446.33	0.34	2566.31
70B3S-HO	70	29924.59	16.33	3600	28907.37	3.40	3578.14
100B3S-HO	100	51588.87	30.33	3600	47776.70	7.39	2918.25
200B3S-HO	200	145122.00	47.19	3600	131049.00	9.70	3600
10B3S-HE	10	3545.59	0	0.96	3545.59	0	164.40
50B3S-HE	50	19354.48	7.93	3600	19354.48	0	3017.53
70B3S-HE	70	30017.61	14.68	3600	29265.85	2.50	2893.78
100B3S-HE	100	52163.19	30.33	3600	50032.20	4.09	3491.64
200B3S-HE	200	160172.83	54.12	3600	139975.69	12.61	3600

5 Conclusions

In this work a Variable Neighborhood Search and Branching matheuristic for the 3-D Yard Allocation Problem for Break Bulk Cargo has been proposed and tested on real-world instances arising from the port yard of Vitoria (Espirito Santo, Brazil). The numerical results, although preliminary (10 instances), are encouraging since show that the VNSB is able to find on average better solutions than CPLEX and in less CPU time. In this way it is also possible to face real scale size instances for which CPLEX was in difficulty. Future work concerns an experimental campaign on a wider set of instances to validate the performances of the VNSB proposed.

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