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Planning container transfers in a multi-terminal port: models, methods and preliminary results

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1 Introduction

The large majority of non-bulk cargo worldwide is moved by container ships. In the global transport network, container ports act as intermodal interfaces, where containers are transferred between foreign-going ships, feeder ships, barges, trains and trucks.

Nearby container ports are competing for traffic. Different factors have been identified as contributing positively to the attractiveness of a port, among which the operational efficiency of its terminals [5]. Container terminal operations have received considerable attention in the literature in recent years [4]. Many studies focus on one computationally challenging problem that occurs in one terminal, e.g. berth planning, quay crane scheduling, storage space allocation, etc. A few studies, such as this one, consider globally the flow of containers through a set of terminals in a port [3, 2].
Computing an optimized container flow in a transshipment hub over a set of container terminals, and a set of consecutive periods, is studied in [3]. Decisions are taken for groups of containers, i.e. sets of containers exchanged between two ships. Terminals and yard allocations of group of containers have to be planned, which indirectly assign visiting terminals for calling vessels. The objective is to minimize inter-terminal and intra-terminal handling costs.
The strategic problem of spreading a set of cyclically calling vessels over a set of terminals owned by an operator and allocating time windows to them is studied in [2]. The objectives are to balance the quay crane workload among the terminals over time and to minimize inter-terminal transfers. Three kinds of container flows are taken into account: between vessels, from hinterland to vessels and between terminals. A relaxed berth allocation problem as well as a relaxed crane assignment problem are solved within the global problem.

We propose a multi-periodic global tactical model to handle container transport vehicles - ships, barges, trains and trucks - and their containers. The primary objective is to minimize the weighted sum of tardiness of ships and trains, which have a due date and a deadline: time windows are expected as input. Unlike the model proposed in [3], yard allocations are implicit in our model, but decisions concerning ships, trains, and trucks are explicit. A constraint limiting the quantity of containers transferred between terminals corresponds to a second objective. Only few hypotheses on

the type of equipment used by the terminals, on their layouts, and on the port layout, are made. The model can be applied to various port and terminal layouts.

2 Problem description

Hereafter, the word *ship* will denote a foreign-going ship, a feeder ship or a barge. The word *vehicle* will denote a ship, a train, or a group of trucks. In the proposed model, trucks are grouped by time windows. A *handling zone* is a part of a terminal set up to handle a mode of transport.

Containers are treated by batches. A container batch is defined as a set of containers unloaded from one vehicle and loaded to another one. Operations on container batches are: unloading/loading from/to a vehicle, storage in a terminal, and inter-terminal transfers. All handling of container batches have to be completed with the available resources. The problem is formulated as a Mixed-Integer Linear Program (MILP), with binary variables indicating whether:

- ship v is handled in zone (berth) z with n cranes for period t,
- train v is handled in zone (rail tracks) z for period t,
- batch b is loaded (resp. unloaded) at terminal c.

Real non-negative variables account for operations on batches:

- number of containers from batch b loaded (resp. unloaded) in terminal c during period t,
- total number of containers from batch b stored in terminal c at the end of period t,
- number of containers from batch b sent from terminal c to terminal c' during period t.

There are many sets of constraints, among which:

- Some vehicles (e.g. foreign-going ships) must be handled continuously in only one zone.
- In a zone for ships, there are at most two ships handled at the same time.
- Speed of loading and unloading container batches for a ship depends on the number of assigned cranes (most of the time non linearly).
- The number of cranes operating simultaneously in a zone for ships is limited.
- In a zone for trains, the number of trains can not exceed the number of tracks.
- The number of TEU stored in a terminal can not exceed its storage capacity.
- The number of containers transferred between each couple of terminals per period is limited.

3 Solving methods

Apart from direct solving by a state of the art MIP solver, the following three methods were tested. A pre-assignment heuristic is proposed for instances where decisions on assignments of ships or trains to terminals have to be done. After a pre-assignment, the set of possible handling terminals of each ship and train has only one element, and the size of the MILP for planning container transfers is reduced. The pre-assignement problem is formulated and solved as a specific MILP. Each time a

pre-assignment has been obtained, a MILP for planning container transfers is sent to the solver with a time limit. This heuristic stops when either a solution of value 0 (therefore optimal) has been found or a global time limit has been reached.

A greedy constructive heuristic based on two decomposition levels: by modes of transport and by time windows is under investigations.

A branch-and-price was first tried but two major difficulties could not be overcome.

- Linear program re-optimizations were slow: after adding one or several generated column(s) to a restricted master linear program, too many simplex iterations were needed to obtain new dual variables, which was not caused by degeneracy.
- Lagrangian dual bounds required too many column generation iterations to come close to already optimal (according to the numerical precision) linear-relaxation bounds of the restricted master problems, and stabilization was not obtained.

4 Numerical results

Numerical experiments on more than 2000 diversified instances were performed. Instances were randomly generated by a parameterizable software developed for our researches and inspired by [1]. Parameter values were chosen to produce realistic instances, matching figures found in scientific articles [1], or given by terminal managers. Results are given here for a configuration with 2 specialized terminals, involving one maritime terminal and one hinterland terminal (similar to a future configuration in the port of Le Havre). Other configurations have from 1 to 3 identical general-purpose terminals, each one equipped to handle ships, trains and trucks. Annual traffic is 2, 3, 4 or 5 millions of TEU, planning horizon is 5 or 7 days and period length is 1 or 2 hours. Instances were generated with container flows similar to the ones flowing through the largest European container terminals.

In the table, results are grouped by generation parameters, by instance categories, by sub-categories and by values of η, which is a multiplier stretching all vehicle time windows, i.e. which increase their deadlines. The column *Count* gives the numbers of instances. An instance is in the category *Solved* if an optimal solution and a proof of optimality have been obtained, or if a proof of infeasibility has been found. In the other cases, that is, without a feasible solution or a with a feasible solution but no proof of optimality, an instance is counted as *Unsolved*. The MIP solver is IBM ILOG CPLEX 12.6. Computations were done on personal computers, each one having an Intel Xeon CPU at 3 GHz and 8 Go of RAM. Time limit is 7200 seconds per instance.

Almost 98% of the 1600 instances with one general-purpose terminal or 2 specialized terminals are solved within the time limit. Cut generation performs well since most of the time it strongly decreases the number of binary variables with fractional values at the root node. Instance infeasibility is relatively quickly detected. Instances without tardiness are on average more quickly solved than those with. Solving an instance with tardiness requires generally more branching. Variance on solving time is larger for instances with tardiness.

By switching η from 1.25 to 1.5, unfeasible instances sometimes become feasible, and instances with tardiness sometimes become without, because time windows of groups of trucks are widened. This shows that the maximum number of operations per period in a terminal is constraining. Keeping other parameters constant, increasing η from 1.25 to 1.5 generally results in an increase of computation times.

Generation parameters	Category		η	Count	Computation time			
					min.	avg.	max.	var.
2 specialized term., $4\overline{\text{M}}$ annual TEU, 120 periods of 1 h[1]	Solved[2]	No tardiness	1.25	59	27.9	259.7	5672.6	521910.7
			1.5	59	43.3	209.5	657.7	24053
		Tardiness	1.25	9	165.6	617.6	2113.1	386685.1
			1.5	14	163.5	1439.8	6238.6	3740588.7
		Inf.	1.25	24	1.1	5.3	6.9	2.6
			1.5	15	1.3	5.7	8.2	4.9
	Unsolved	Feas. sol.	1.25	5	7200			
			1.5	6				
		No feas. sol.	1.25	3				
			1.5	6				
2 specialized term., $4\overline{\text{M}}$ annual TEU, 168 periods of 1 h[1]	Solved[2]	No tardiness	1.25	28	51	167.5	850.6	25055.4
			1.5	30	54.7	258.2	1485.7	84386.5
		Tardiness	1.25	11	64	621.6	2315.6	536413.4
			1.5	12	227	1008	2301.1	579944.1
		Inf.	1.25	60	2.1	10.1	219.1	758.8
			1.5	56	2.4	7	14.2	18
	Unsolved	Feas. sol.	1.25	1	7200			
			1.5	2				

[1] Periods among which arrivals are drawn.
[2] Found an optimal solution and a proof of optimality, or a proof of infeasibility.

Table 1: Results of direct solving by a solver over sets of instances 6 and 8

Note that, when an instance is feasible, there is often a very large number of possible values for binary variables providing optimal solutions, and most of the time, the MIP for planning container transfers is solved within the time limit, as long as it is not too large and if there isn't too much tardiness among ships and trains.

The direct solving method is unsuccessful with instances having several general-purpose terminals and vehicles for which terminal assignment decisions must be made. These instances allows us to test the pre-assignment heuristic. Almost 95% of the 350 first instances with several general-purpose terminals are solved by the pre-assignment heuristic, whereas only about 11% are directly solved. The solving rates of the 50 last instances fall respectively to 52% and 0%. For these instances, even after pre-assignment, the MILP is still too large, and limits on the solving capability by a MIP solver in the allowed time are met.

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