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Exact and heuristic methods for placing ships in locks

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ABSTRACT

The ship placement problem constitutes a daily challenge for planners in tide river harbours. In essence, it entails positioning a set of ships into as few lock chambers as possible while satisfying a number of general and specific placement constraints. These constraints make the ship placement problem different from traditional 2D bin packing. A mathematical formulation for the problem is presented. In addition, a decomposition model is developed which allows for computing optimal solutions in a reasonable time. A multi-order best fit heuristic for the ship placement problem is introduced, and its performance is compared with that of the left-right-left-back heuristic. Experiments on simulated and real-life instances show that the multi-order best fit heuristic beats the other heuristics by a landslide, while maintaining comparable calculation times. Finally, the new heuristic's optimality gap is small, while it clearly outperforms the exact approach with respect to calculation time.

1. Introduction

When entering or leaving a port, ships often pass one or more locks. So do barges travelling on a network of waterways. The locks provide a constant water level for ships while loading or unloading at the docks, or they control the flow and the level of inland waterways.

The growing number of container shipments causes high demands on sea ports (Wiese, Suhl, & Kliewer, 2010). Improving the ship handling can reduce their *time in port* and make a seaport economically more attractive, engendering a strong competition between (geographically close) seaports (Bish, 2003; Chen, Bostel, Dejax, Cai, & Xi, 2006; Cullinane & Khanna, 2000; Günther & Kim, 2006). While many aspects of handling ships and containers in seaports have been extensively researched (Stahlbock & Voß, 2008), one key component of the port's infrastructure has received little attention: the locks. A suboptimal usage of the locks' capacity can however strongly increase the handling times of ships. When the lock is unable to transfer a given ship in time, this ship could miss its time window at the terminal, leading to a strong increase in total time in port and a reduced efficiency of the terminal. Improved operation of these locks can therefore play an important role in increasing a port's efficiency and economical attractiveness.

The expected increase of intermodal transport is a major incentive for improving lock efficiency on inland waterways (European Commission, 2009, 2011). Intermodal transport is the combination of multiple transport modes in a single transport chain without a change of container for the goods. Inland navigation is a most promising transport mode in the intermodal chain, with its availability of access capacity in the network and environmentally friendly character as most important benefits. This is especially true in the Belgian and Western-European context, where inland waterways play a crucial role in the hinterland access of major sea ports (Notteboom & Rodrigue, 2005). Increasing the efficiency of (intermodal) barge transport through better lock operations is therefore a key issue in supporting future freight flows and increasing the market share of inland navigation.

2. Literature review

Only a small number of academic papers focus on lock planning. Wilson (1978) investigates the applicability of different queuing models for lock capacity analysis. The research shows that good queuing models exist for single chamber locks, but not for locks with parallel chambers. Some of the other research has focussed on the Upper Mississippi River (UMR). On that river, barges are joined together into tows for transport, which then need to be transferred by single chamber locks that are often smaller than the tow itself. The tow is split into different groups of barges and these groups are transferred one at a time, after which they are rejoined for the next phase of their travel. Nauss (2008) presents

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Nomenclature

Sets

N	set of ships that need to be placed, $N = \{1, 2, \ldots, n\}$
M	set of lockages (bins) available, $M = \{1, 2, \ldots, m\}$, where m should be a sufficiently large number, e.g. $m = n$ or equal to an appropriate upper bound
$MOOR_i$	set of ships to which ship $i \in N$ is allowed to moor

Parameters

W, L	width and length of the chamber (integer)
w_i, l_i	width and length of ship $i \in N$ (integer)
dF_i, dB_i	minimal distance between ship $i \in N$ and the front/back of the chamber
sW_{ij}, sL_{ij}	minimal safety distance between ships $i \in N$ and $j \in N$ when they are adjacent, or laying behind each other
$ship_0$	represents the left quay of the chamber: $x_0 = 0$, $y_0 = 0$, $w_0 = 0$, $l_0 = L$
$ship_{n+1}$	represents the right quay of the chamber: $x_{n+1} = W$, $y_{n+1} = 0$, $w_{n+1} = 0$, $l_{n+1} = L$
K	relative cost of the number of lockages

Variables

x_i, y_i	integer variables that define the x and y position of ship $i \in N$ in the chamber (lower left corner of ship)
$left_{ij}$	binary variable that indicates if ship $i \in N$ is left to ship $j \in N$ ($left_{ij} = 1 \Rightarrow x_i + w_i \leqslant x_j$)
b_{ij}	binary variable that indicates if ship $i \in N$ is behind ship $j \in N$ ($b_{ij} = 1 \Rightarrow y_i + l_i \leqslant y_j$)
ml_{ij},mr_{ij}	binary variables that indicate if ship $i \in N$ is moored to ship $j \in N$'s left, respectively right, side
z_k	binary variable that indicates whether lockage $k \in M$ is used or not
f_{ik}	binary variable that indicates whether ship $i \in N$ is processed in lockage $k \in M$ or not
v_{ij}	binary variable, 0 when ship $i \in N$ and $j \in N$ are processed in the same lockage, 1 otherwise

optimal sequencing of tows/barges for single chamber locks with set-up times. The approach allows one tow/barge to be transferred at a time. Furthermore, it considers all tows/barges to be present at the lock before the first lockage. A simulation model for comparing different strategies to relieve congestion problems on the Upper Mississippi river is presented in Smith, Sweeney, and Campbell (2009). The strategies aim at increasing the throughput of the locks and a simulation tool was built for validating them. Smith et al. (2011) further increases the performance of these locks using more complex decision rules based on heuristics and MIP models.

Another part of the lock scheduling literature focusses on locks with (parallel) chambers capable of transferring several ships together. A recent contribution (Verstichel & Vanden Berghe, 2009) deals with planning a lock with three parallel chambers, two of which are identical. The presented approach allows more than one ship to be transferred in one chamber at the same time, and considers independent operation of the chambers. A problem specific left-right-left-back heuristic combined with a late acceptance hill-climber generated good quality results. Scheduling the chamber operations of a lock with identical parallel chambers is investigated in Verstichel, De Causmaecker, and Vanden Berghe (2011). The contribution identifies the problem as the identical parallel machine scheduling problem with sequence dependent setup times and release dates, and presents a mathematical model. Both inland locks with fixed processing times and sea port locks with ship dependent processing times are considered. A meta-heuristic approach to the problem is presented, and its performance is compared with that of the first-come-first-served decision rule. Coene, Spieksma, and Vanden Berghe (2011) focus on planning lock operations without considering the actual placement of ships within the chamber.

The present paper considers locks with at least one, but possibly multiple parallel chambers with different properties. Each chamber has a limited capacity, based on its dimensions, and a certain lockage duration, i.e. the time needed to change the water level in the chamber from the level on one side to the level on the other side. Chambers with identical dimensions and lockage durations are of the same chamber type. Therefore, when some of the chambers are identical, a lock will consist of fewer chamber types than the number of chambers. When planning transport through a lock, different issues may arise. The time needed to transfer a number of sea ships, for example, depends on their size and manoeuvrability. Positioning the ships in the chamber may even take longer than the actual lockage operation of the chamber, particularly when transferring large ships that require tugboats. When only inland ships are transferred, the time needed to position the ships can be considered constant as these ships are much smaller and can easily be positioned inside the chamber. The time needed to position the ships inside the chamber could even be included in the lockage time of the chambers. Also strategies for operating parallel chambers differ. Some locks use paired chambers, which must be operated simultaneously, while other systems allow independent operation of the chambers. In spite of these different approaches, all aforementioned cases require solutions to the ship placement problem. When several ships can be transferred simultaneously in one lockage, a better ship placement procedure may strongly increase the lock's efficiency. Two examples where locks play a crucial role in the transportation chain are the Port of Antwerp and the Albertkanaal in Belgium.

This paper introduces a mathematical model for the ship placement problem and compares three algorithms: (i) an exact decomposition based integer programming approach, (ii) a modified left-right-left-back heuristic (Verstichel & Vanden Berghe, 2009), and (iii) a multi-order best fit heuristic. The main contribution of part (i) is the in-depth analysis of the ship placement model and its characteristics, and the introduction of a decomposition method generating optimal solutions, even for very large instances.

Section 3 introduces the details of the problem and a mathematical model for the ship placement problem. Section 4 describes the three solution approaches that were applied to the problem. The experimental setup and results are discussed in Section 5, followed by the conclusions in Section 6.

3. Problem definition and model

3.1. Problem definition

Ships constitute the first major component of the ship placement problem. They are characterised by a width w_i, and a length ℓ_i. By assuming rectangular-shaped ships, we simplify the evaluation of the placement constraints. This simplification is common practice, as the exact shape of the ships is often not available to