European Journal of Operational Research 253 (2016) 298–313

Contents lists available at ScienceDirect

European Journal of Operational Research

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

Discrete Optimization

Scheduling cranes at an indented berth

Marie-Anne Beens, Evrim Ursavas*

Department of Operations, Faculty of Economics and Business, University of Groningen, Nettelbosje 2, 9747 AE Groningen, The Netherlands

ARTICLE INFO

Article history:
Received 24 July 2015
Accepted 23 February 2016
Available online 2 March 2016

Keywords:
Maritime logistics
Crane sequencing
Crane scheduling
Container terminal operations
Indented berth

ABSTRACT

Container terminals are facing great challenges in order to meet the shipping industry's requirements. An important fact within the industry is the increasing vessel sizes. Actually, within the last decade the ship size in the Asia–Europe trade has effectively doubled. However, port productivity has not doubled along with the larger vessel sizes. This has led to increased vessel turn around times at ports which indeed is a severe problem. In order to meet the industry targets a game-changer in container handling is required. Indented berth structure is one important opportunity to handle this issue. This novel berth structure requires new models and solution techniques for scheduling the quay cranes serving the indented berth. Accordingly, in this paper, we approach the quay crane scheduling problem at an indented berth structure. We focus on the challenges and constraints related to the novel architecture. We model the quay crane scheduling problem under the special structure and develop a solution technique based on branch-and-price. Extensive experiments are conducted to validate the efficiency of the proposed algorithm.

1. Introduction

Approximately 90% of the world's trade is conducted and processed by the international shipping industry, making international shipping the leading carrier of international trade (Tierney, 2014). A key aspect of the shipping industry is container shipping. Containers are designed for easy and rapid shipment of cargo. An important player in container shipping is the container terminals. A container terminal is a facility where cargo containers are transshipped between container ships and land vehicles for onward transportation, and containers are temporarily stored for further transportation. Globalization and an ever-increasing demand for goods have led to an increase in container shipping. Along with high competition and lower margins, what can directly be noticed in the sector is the increasing vessel sizes to benefit from economies of scale. In fact, since 2007 the ship size in the Asia–Europe trade has effectively doubled. However, port productivity has not been able to keep up with this increase. According to Maersk Lines, on an Asia–Europe round-trip the time spent in port (one vessel on average) has increased from 12 days (2007) to 18 days (Maersk Line Report, 2014). These facts have underlined the need for more efficient terminals in order for shipping companies to maintain a competitive position. The main objective in an efficient terminal is to be able to service the vessels within the time limits agreed upon with the shipping companies. Reducing the agreed limits requires the minimization of time spent in port by container ships: the berthing time. In order to minimize the berthing time it is necessary to handle all loading and discharging processes fluently and to minimize the total container traveling distance in the yard. Adding more resources and most critically the handling equipment that is quay cranes is one important solution to the problem. However, there is above all a physical limit (length of a vessel and safety distances between adjacent cranes) as to the number of cranes a vessel can be assigned to. The issue is that the length of vessels has not increased linearly with their TEU intake, as they have got wider, deeper and stacked higher instead. Therefore, in order to meet the industry standards and decrease berthing time a game-changer in container handling is required as Maersk Line CEO Soren Skou has put it: 'We continue to build ships that are bigger and bigger, and if we can't get the containers off faster, the whole thing will come to a grinding halt' (Tirschwell, 2015).

Indented berths are recently brought as a solution to this severe problem. Upon arrival at port a container ship is assigned a berth with quay cranes, which load and unload containers to and from the ship. Indented berths enable the ship to be unloaded from two sides simultaneously with two rows of quay cranes on opposing sides, whereas traditional berths only allow loading and unloading from one side. Hence, indented berth increases the ship-to-shore interface length with the vessel so the vessel can be simultaneously handled from both sides. This new architecture requires new models and solution techniques to be built as the setting has its own characteristics, challenges and restrictions. We will briefly summarize these as follows:

* Corresponding author. Tel.: +31 50 363 7086.
E-mail address: e.ursavas@rug.nl (E. Ursavas).

http://dx.doi.org/10.1016/j.ejor.2016.02.038
0377-2217/

Firstly, at an indented berth quay cranes are designed in a way that the arm can ascend when it is to pass the quay cranes on the opposite side. Due to this design feature the quay cranes on opposing sides of the indented berth are free of non-crossing constraints. Cranes on the same side and on the opposing sides should be handled differently together with specific restrictions such as the avoidance of working simultaneously on the same bay on the opposing sides.

Secondly, an important characteristic of indented berth operations is the importance of vessel stability which if not treated appropriately could lead to disasters. A ship contains a selection of add-on active stability systems, allowing it to adjust to the effects of waves and wind gusts. However, these do not increase the stability of the ship in calm seas. Since in indented berths quay cranes are able to handle the ship simultaneously from two sides, there is increased activity as compared to traditional berths. This increases the risk of an unbalanced ship. Balance constraints ensure that the difference between the number of containers on the left and the right sides of the ship is within a certain safe range. This requires the container load to be distributed equally along the width of the ship during the loading and unloading process. The balance constraints are forced by a certain latitudinal-balance threshold and restrict the number of containers on one side of the ship being significantly larger than the other side, preventing to have an incline and eventually, to tilt.

Another difference in an indented berth layout stems from the fact that the importance of minimizing the distance a container has to travel between vessel and yard block becomes more significant in the planning of the cranes. For an indented berth the distance of a task depends on the quay crane it is assigned to, whereas in a traditional berth the distance of a task is approximately similar for all quay cranes. This characteristic of indented berths enables to choose a quay crane to unload or load a container with the smallest distance from ship to yard block in order to minimize the total distance and provides opportunities for better solutions. This indeed requires the consideration of distances while planning the operations.

Finally, simultaneously operating quay cranes is indeed useful in shortening the berthing time for a ship. However, the suggestion that boosting the speed or number of quay cranes operating on a ship in order to increase the speed and productivity of the loading and unloading process is not necessarily the optimal solution, since more or faster operating quay cranes increase the risk of congestion on the quay crane rail tracks and in the terminal. Containers that are being discharged from a ship are transshipped to a yard block and containers that are being loaded onto a ship come from a yard block. A major issue is the avoidance of congestion at yard blocks. In comparison to a traditional berth layout, a system focused on simultaneously operating quay cranes and decreasing congestion is essential to consider in an indented berth setting.

Previous literature has not yet attended the indented berth layout problem considering the characteristics and restrictions stated above. Consequently, this paper contributes to the literature by creating a novel model for the quay crane scheduling problem considering the mentioned specific features of a terminal with an indented berth layout. We aim to minimize the distance traveled within the storage yard while adhering to the time limit contracted with the shipping company and the restrictions imposed with the novel setting. We have further developed a solution technique based on branch-and-price to solve the described problem.

Remaining parts of this paper will be organized as follows: Next section provides an overview of relevant port operations in an indented berth. Section 2 overviews the main findings of previous research. In Section 3, the compact mathematical formulation for the indented berth problem is presented, after which a branch-and-price algorithm is proposed to solve the problem. Thereafter, numerical experiments on both the compact model and the branch-and-price algorithm are performed in order to compare results and performance. We further discuss concepts important to the industry for implementing the new layout. In the last section, we conclude this paper.

1.1. Port operations at an indented berth layout

Before arrival at the terminal, the shipping company provides the stowage plan. This stowage plan contains information about the location and destination of tasks. The expected vessel turn around time, that is the time that the vessel can sail to other destinations is agreed upon by contracts. Given these, upon arrival of the vessel at the terminal, the ship is berthed where loading and unloading tasks can be performed by quay cranes positioned on two sides of the ship. Quay cranes are mounted on a rail track at the quay and can move parallel to the ship. It is not possible for a quay crane to switch sides or cross the path of a quay crane mounted on the same side. As mentioned earlier, quay cranes are designed in a way that the arm can ascend when it is to pass quay cranes on the opposite side of the ship. This feature allows opposing quay cranes to be free from non-crossing constraints. However, simultaneous operations on the same bay from opposing sides should be avoided. Once containers are unloaded from the ship, the quay cranes place containers onto a vehicle for transportation to a determined yard block. A yard block consists of two parts: one part where containers that are unloaded from the ship are stacked and one part where containers that will be loaded onto the ship are stacked. A container terminal with an indented berth structure is illustrated in Fig. 1.

Transportation between ship and yard block is performed by automated vehicles or trucks. The distance between a yard block and the ship is affected by the quay crane handling a container. If a container is handled by a quay crane on the opposite side of the yard block, the distance is larger than if the container is handled by a quay crane on the same side as the yard block. In an indented berth there are two sizes of yard blocks. An indented berth is considered to have four accompanying yard blocks: two adjacent to the ship and two located in the yard at the front of the ship. Yard blocks that are adjacent to the ship are smaller than yard blocks located in the yard. Although it may differ across different terminals, it is assumed that yard blocks in the yard have a width of 6 rows of containers and can be up to six levels of containers high depending on the gantry crane used. Adjacent yard blocks have a length of 20 containers from end-to-end, while yard blocks in the yard can have up to 30 containers from end-to-end. The number of unloading and loading tasks at a particular yard block is stated in the stowage plan. At a yard block, yard cranes handle containers. Yard cranes can lift containers from trucks onto their assigned yard block and can place containers from the yard block onto trucks for further transportation. Congestion at yard blocks can be caused if a large amount of yard crane and truck activity has to be carried out at one yard block at the same time. After a task is finished, trucks are replaced in their original position allowing them to be used to perform subsequent tasks.

2. Literature review

Research focusing on container terminals has a long history. In recent years, there has been an increasing amount of literature regarding the quay crane scheduling problem with respect to spatial constraints and clearance constraints. However, in line with its novel architecture relatively very few papers on indented berths have been published. In the following section major research conducted on quay crane scheduling problem, and the quay