ARTICLE IN PRESS

Transportation Research Part D xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Transportation Research Part D

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

# The waterway ship scheduling problem

Eduardo Lalla-Ruiz [a,*], Xiaoning Shi [a], Stefan Voß [a,b]

[a] *Institute of Information Systems (IWI), University of Hamburg, Germany*
[b] *Escuela de Ingeniería Industrial, Pontificia Universidad Católica de Valparaíso, Chile*

ARTICLE INFO

*Article history:*
Received 30 November 2015
Revised 5 August 2016
Accepted 20 September 2016
Available online xxxx

*Keywords:*
Waterway ship scheduling problem
Maritime shipping
Container terminal

ABSTRACT

One of the most important issues in port connectivity refers to the availability of accessible waterways and their traffic management. This puts a lot of pressure especially into capacity restricted transport corridors, where their inefficient use may not only result in a loss of the port competitiveness but also in an increase of the volume of ship emissions polluting the environment. In this context, the Waterway Ship Scheduling Problem is proposed; its goal is to schedule incoming and outgoing ships through different waterways for accessing or leaving the port in such a way that the ships' waiting time is minimized. This objective allows, on the one hand, to avoid bottlenecks or congestions through scheduling the waterway traffic, and on the other hand, reduce vessel emissions while they are waiting at the anchorage either for entering or leaving. A mathematical model and heuristics are proposed. Real scenarios based on the Yangtze Delta (Shanghai) are tackled for assessing the performance of the heuristic and the improvement upon real-world terminal operations.

## 1. Introduction

The maritime traffic growth forces port operators to efficiently reduce the ships' waiting time when accessing their infrastructures if they want to increase or maintain their market share (Verstichel et al., 2011), reduce ship emissions (see Du et al., 2011, 2015) that contribute to increase greenhouse gases and harmful pollutants, and upgrade the port position in the port hierarchy through enhancing the port accessibility (Caldeirinha and Felício, 2014). In this regard, as indicated by Notteboom (2006), 93.6% of the delayed schedules are attributable to port access and terminal operations. This characteristic becomes even more relevant at some container terminals like in the port of Shanghai, where – according to practitioners – there is a multitude of ships daily requiring to pass through the Yangtze Delta waterways. Therefore, since the waterways play an important role at some maritime container terminals (Notteboom, 2008), it is sought to efficiently use them in order to avoid bottlenecks or congestions that may be translated into a loss of competitiveness. Moreover, the use of inland waterways as a transportation mode at container terminals is becoming even more relevant when we consider its increasing integration with other transport modes within multi-mode freight network schemes (Lowe, 2005, UNESCAP[1]). This close intermodality pursues to cope with the spatial or logistic restrictions that appear at some container terminals and it adds to the issues to be dealt with in port connectivity in the globalized economy.

From a green-logistics standpoint, on the one side, terminal operators are interested in reducing ship emissions while maintaining the quality of the service and, on the other side, shipping companies require smooth services to avoid unnec-

---

* Corresponding author.
*E-mail addresses:* eduardo.lalla-ruiz@uni-hamburg.de (E. Lalla-Ruiz), xiaoning.shi@uni-hamburg.de (X. Shi), stefan.voss@uni-hamburg.de (S. Voß).

[1] United Nations Economic and Social Commission for Asia and the Pacific, Transport Division (TD) (UNESCAP, 2004).

http://dx.doi.org/10.1016/j.trd.2016.09.013
1361-9209/© 2016 Elsevier Ltd. All rights reserved.

Please cite this article in press as: Lalla-Ruiz, E., et al. The waterway ship scheduling problem. Transport. Res. Part D (2016), http://dx.doi.org/10.1016/j.trd.2016.09.013

essary waiting times that cause a negative economic and environmental impact related to fuel consumption and route timing. Some works in the specialized literature have studied the relationship between the ships' waiting time and their emissions. Du et al. (2011) indicate that the waiting time of the ships has an important influence on the volume emissions, where having flowing operations can help shipping companies to reduce emissions as well as help ports to have control over that. In the same line the work by Kontovas and Psaraftis (2011) investigates the reduction of emissions in maritime intermodal container networks, indicating that one of the main alternatives to reduce $CO_2$ emissions is related to the reduction of the vessel waiting time. Song (2014) studies the ship emissions inventory ($CO_2$, $CH_4$, $N_2O$, $PM_{10}$, $PM_{2.5}$, $NO_x$, $SO_x$, CO and HC) and their associated social cost in the Yangshan port at the south of Shanghai (China). In their work they include the waiting of the ship at the anchorage as well as at the berth as segments for evaluating the ship emissions. Their results show that although waiting at the berth has a greater impact than waiting at the anchorage, both activity modes result in sources of emissions. Fagerholt et al. (2010) in the context of shipping routes indicated that the more vessels' waiting time the more the potential to reduce fuel consumption increases; this highlights the importance that waiting times have on consumption and emissions. Therefore, improving the waterway access operations by avoiding unnecessary waiting time at their entrance may lead not only to operational and social cost savings but also to an enhancement of the level of environmental quality of service through minimizing emissions.

In maritime shipping delayed schedules attributable to port access affect terminal productivity especially at some high-congested terminals, that are largely influenced by port access operations related to waterways. To be generic, a waterway can be defined as a capacity restricted transport corridor filled with water, *e.g.*, a passage within inland rivers, lakes or bays which are navigable. A typical waterway consists of navigable waters, navigational aids and water conditions. Often natural as well as artificial waterways may be referred to as capacity restricted transport corridors, depending on their specific characteristics. They have to meet several conditions so as to serve the ships. First of all, an eligible waterway should provide sufficient depth. Secondly, the width of the waterway is also a crucial criterion. Usually, a waterway is two-directional and its width should exceed the sum of the breadth of the two navigating ships at the opposite direction with additional abundant width for the sake of safety, but occasionally it just refers to the isolated passing of individual vessels.

Only a few works focus their attention on waterway scheduling. Dai and Schonfeld (1998) discuss the estimation of waterway delays using metamodels and queuing theory. Taylor et al. (2005) develop a simulation-based software system for barge dispatching and boat assignment in an inland waterway. Some other works are more related to the use of locks. Smith et al. (2009) analyse the Upper Mississippi River waterway. This is a major inland waterway that includes 29 locks. They present a discrete simulation model as a suitable procedure for improving the practice prevailing first-come first-served strategy used. Smith et al. (2011) propose complex decision rules based on a heuristic scheduler and a mathematical integer problem for improving the performance of the locks. Verstichel et al. (2014) study the positioning of the ships into lock chambers; they present a mathematical formulation and a solution approach for solving it. Other works focus their attention on the traffic planning on canals. Günther et al. (2010, 2011) deal with the bidirectional ship traffic on the Kiel Canal. They consider the canal as an alternating collection of canal segments and sidings. They present a mathematical formulation for designing the liner route and shipping networks. The aim of their model is to minimize the total passage time of ships, where this time includes the lock and siding waiting times. Yang et al. (2014) present an integer programming model to optimize the container liner network on the Yangtze River. They consider the Yangtze constrained only to a single water channel rather than several alternatives and all ports queue alongside the waterway. Their approach aims to reduce the transportation costs, that are the operation and fuel costs of the selected route. They consider the same operation times in each port. Ulusçu et al. (2009) study the traffic along the Istanbul Strait and develop an algorithm for scheduling the incoming ships for the specific considerations of the strait.

Despite the fact that in the related literature some works address one or the other waterway scheduling problem, the proposed approaches are restricted to the specifications of the studied waterways or designing the routes for visiting terminals along them. In this regard, in this work one of our goals is to present a more general approach for addressing the scheduling of the traffic along the waterways. Moreover, this concept also allows us to address the specific logistic scenario that takes place at the entering waterways of the Shanghai Port (China).[2] An entrance waterway is one kind of waterway that connects a sea or inland river main waterway and the harbour water. It is widely acknowledged that one of the criteria to judge a port is its connectivity and it may be operationalized in a simplified way by means of its water depth. However, if one port does not have an entrance waterway with good depth and width condition, ships with large draft still cannot enter no matter how deep the berth-side is. That is why an entrance waterway is of great importance regarding connectivity. For example, the Yangtze Estuary Deep-water waterway as a main entrance of Shanghai port went through three complex and large-scale regulatory projects. Its original depth was 7 m (1998) which seriously restricted the development of the Shanghai shipping industry. Finally it reached a depth of 12.5 m (2010) which permits the passing of the fifth and the sixth generation of maritime container ships.

The previous discussions clearly draw the economical, operational, and environmental importance that scheduling ships along waterways has. This leads to the need of mathematical models and solution approaches for appropriately addressing this issue. With this goal in mind, the main contributions of this paper are:

---

[2] Due to the distance between the different areas of the Port of Shanghai, *e.g.*, Waigaoqiao and Yangshan, the problem of accessing the berthing area and terminals are different. In this work, when we refer to Shanghai port, we refer to the Waigaoqiao terminal cluster.

Please cite this article in press as: Lalla-Ruiz, E., et al. The waterway ship scheduling problem. Transport. Res. Part D (2016), http://dx.doi.org/10.1016/j.trd.2016.09.013

- Propose the Waterway Ship Scheduling Problem (WSSP) in order to address the ship scheduling along waterways. This problem is modelled as Mixed Integer Linear Program (MILP) and addressed considering the real-situation taking place at the Yangtze Estuary, Shanghai. In this regard, according to a survey conducted with the Shanghai International Port Group (SIPG), there is a large number of ships applying to pass the waterway per day and a great proportion of them fails to apply for the appropriate time of passing, because of not considering the geographic constraints of the Yangtze Estuary such as draft, breadth and night navigation.
- As Kontovas and Psaraftis (2011) indicate there are common policies used in terminals for reducing the ships' waiting time and, consequently, emissions. Therefore, we develop and assess heuristics based on some common policies used at container terminals. This allows to evaluate the operational and environmental improvement by means of the reduction of the waiting time that can be obtained through the use of more sophisticated techniques such as the simulated annealing (SA) proposed in this work. In this sense, the proposed SA approaches allow to reduce the unnecessary emissions generated during the ships' waiting time. In addition, the comparison with the model implemented in CPLEX and the heuristics shows that the SA is able to provide high-quality schedules which justify its use as part of a decision support system (DSS). In this real application, the DSS would be used for verifying all the ships and modify their time assignments.
- Provide a benchmark suite based on data provided by the container terminal of Waigaoqiao (Shanghai). On the other hand, since this problem can be translated to other scenarios, the benchmark suite includes other problem instances of different dimensions.

The remainder of this paper is organized as follows. Section 2 introduces specific characteristics of the Yangtze Estuary. The mathematical formulation of the Waterway Ship Scheduling Problem is presented in Section 3. In Section 4, the solution approaches proposed for solving this problem are depicted. Afterwards, Section 5 analyses the performance of our proposal in realistic scenarios. Finally, Section 6 provides our main conclusions extracted from the work and suggests several directions for further research.

## 2. Study area: Yangtze Estuary

While the paper tends to formulate in generic terms it seems important to have a specific application in mind which is described in this section.

### 2.1. Basic settings

The Yangtze Estuary is one of the most vital regions in China regarding freight transportation (see Notteboom, 2007; Comtois and Dong, 2007). The Port of Shanghai located in that region is the leading container port in the Chinese mainland. It has presented an average growth of 16.5% on container throughput in the year 2010 (Yap and Lam, 2013) and is the port with the largest container turnover worldwide over the last years (UNCTAD, 2014). In Fig. 1, a geographical map of the estuary is shown; it consists of several waterways like the deep-water waterway also known as the north passage, the south passage, north branch waterway and south branch passage. Of all the above, the north passage and the south passage are the most important, since they are the entrance to the Waigaoqiao container terminals. The north passage which is also called the Yangtze Estuary Deepwater passage has 12.5 m depth of water after three complex and large-scale dredge projects mentioned above. The width of the north passage is a little more than 80 m which to a large extent restricts the capacity of this passage. However, it is still regarded as a two-directional waterway. On the other hand, the south passage is 5.5 m deep and its width is 250 m which is wide enough for any two ships to navigate side by side.

The regular procedures that ships have to perform for passing along the north and south passages can be described using Fig. 2. The passages are divided by two dashed lines, with each passage allowing at most two ships passing through the passage in different directions. This is subject to width, depth and time-dependent conditions. There are two holding areas, *i.e.*, outer anchorage and berth anchorage, for ships in order to await proper tidal conditions or their turn to go through the passages if necessary. Moreover, for assigning a passage to the ships, they are classified by means of their drafts, namely, small ships (up to 7 m) or large ships (more than 7 m). Depending on the type of the ship, the procedure of entering and crossing the assigned passage follows the flowchart shown in Fig. 3. For the small ships, they initially might have to wait at the outer anchorage and then go through the waterway with fewer constraints. Next they wait again at the port anchorage for berthing. Once the assigned berth is available, they will load or discharge the cargo. As soon as they finish the cargo operations, they have to wait at the port anchorage in the holding area for the right time to leave the estuary if necessary. The procedure followed for large vessels is somewhat simpler. Large ships that want to access Shanghai port enter through the north passage because the south one is not deep enough for them to pass. After they pass the waterway eventually after waiting at the outer anchorage, they directly navigate to the specified berth and begin to load or discharge. Once they are ready to depart, the terminal managers have to check the most appropriate time for them to depart. In this regard, the ships might have to stay at the berth until the appointed time of sail.

In the related literature, most works about waterways in China are focused on assessing the capacity by using simulation approaches. Deng et al. (2011) introduce mathematical methods using queuing theory and empirical methods summarized

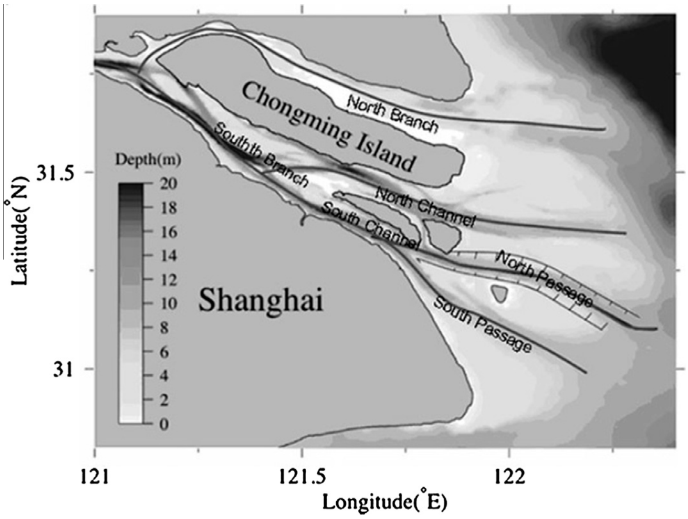

**Fig. 1.** Yangtze Estuary geographical map (De Vriend et al., 2011, p. 1036).

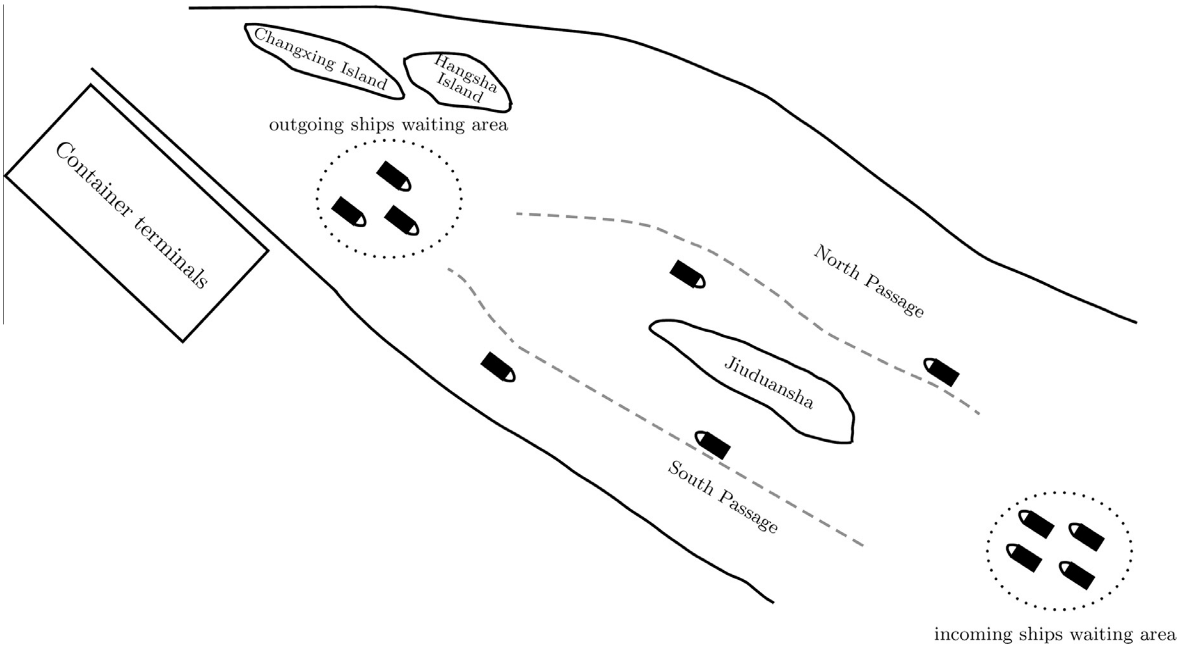

**Fig. 2.** Yangtze Estuary logistic scheme.

by practitioners to calculate the capacity of waterways. The models of Liu et al. (2008) and Ning et al. (2008) for simulating the passage of ships consider different features which are difficult to be reflected by a mathematical model. Yang et al. (2008) describe a simulation model to calculate the capacity of the Yangtze Estuary Deepwater waterway and predict its capacity up to 2024. This model takes into account several factors like geographic conditions, weather conditions and traffic control time, etc. Zhou and Hu (2004) research the sequencing of ships passing through the Yangtze Estuary north passage. To arrange different priorities to different ships intending to pass, Analytic Hierarchy Process (AHP) is applied to consider various factors influencing the priority of ships to pass the waterway.

The in-depth study of this brief literature review points out the necessity of building a DSS to aid the ships to arrange the schedules for passing through the Yangtze Estuary waterways. Therefore, one of the objectives of this work is to propose a solution concept combining experience of practitioners and mathematical methods and provide an important part of a DSS which can serve the ship schedule controller.

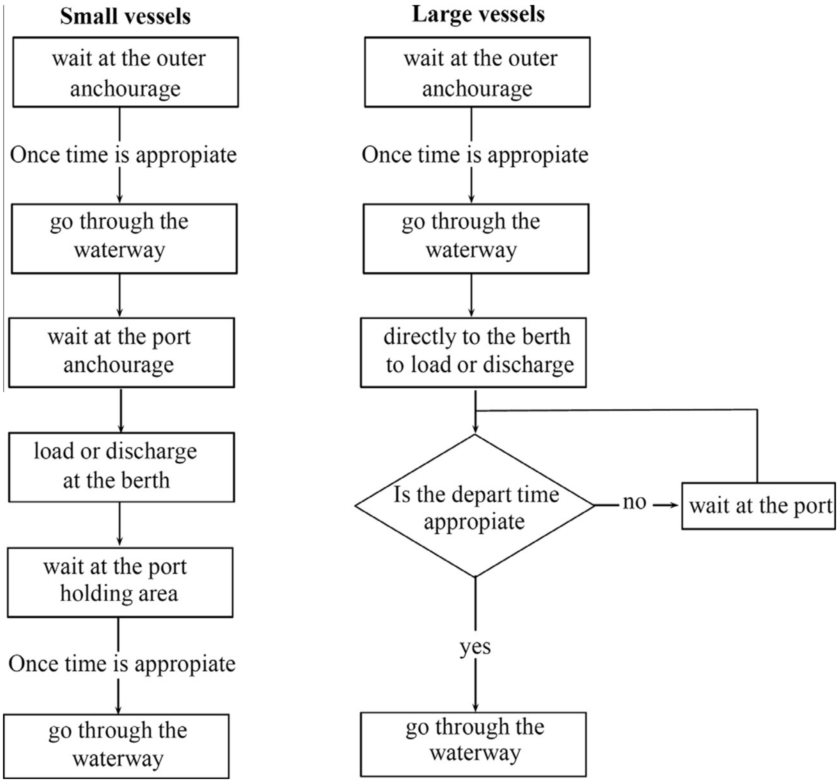

**Fig. 3.** The operation procedure for small and large ships.

### 2.2. Tidal impact

As studied by Du et al. (2015) at some ports the impact of tides (natural rise and fall of sea levels) have an important impact on the vessel schedules when accessing a port resulting in longer waiting times which produce both, operational and environmental burdens. This happens at the port of Shanghai where the tides have a relevant influence on the depth of the waterways. During the two daily tidal peaks the water depth of the waterway will increase to some extent. For instance, at the bottom of the tide the maximal ship draft that can pass through the north passage is 11 m but at the peak of the tide it changes to nearly 13 m. This has to be taken into account since there is a relevant difference between the third and the fourth generation of the loaded container liners.

For appropriately taking advantage of the tidal situation at the Yangtze Estuary, one has to predict its behaviour pattern. In this research, for addressing this issue we consider the tidal data of three observation points, which are Ji Gujiao, Chang Xing and Zhong Jun. These three points are suggested by the geographic experts and the experienced ship schedule controllers. These points have contributed a lot for the practitioners to determine whether a ship can pass the waterway considering the tide.

Taking the tidal conditions into account, complexity issues of the waterway ship scheduling problem at Yangtze Estuary become even more serious. Moreover, under these circumstances, many Estimated Times of Arrival (ETAs) and Estimated Times of Departure (ETDs) could be wrong because the shipping companies fail to consider the tides correctly. That leads to an increment of the ship schedule controllers' workload since they have to check and modify the original schedule reported from the shipping companies. This is one of the motivations for developing a DSS that supports terminal operators for providing feasible schedules by simultaneously taking into account these time-dependent conditions.

## 3. Problem formulation

The Waterway Ship Scheduling Problem (WSSP) considers a set of vessels or ships $V = \{1, \ldots, v\}$, divided into a set of incoming ships $V_1 = \{1, 2, \ldots, v_1\}$, a set of outgoing ships $V_2 = \{1, 2, \ldots, v_2\}$, a set of available waterways $W = \{1, \ldots, w\}$, and a set of time steps $H = \{1, \ldots, h\}$. Since this problem is a daily operational problem we consider a one-day time horizon and the variation of the tide level along this time period. Furthermore, in the WSSP for each ship $i \in V_1 \cup V_2$, there is a given Estimated Time of Arrival at the port, $ETA_i$, Estimated Time of Departure, $ETD_i$, width $w_i$, length $l_i$, draft $d_i$ and, depending on the assigned waterway $k \in W$, a transit time $t_{ik}$. On the other hand, each waterway $k \in W$ has an available time window

Please cite this article in press as: Lalla-Ruiz, E., et al. The waterway ship scheduling problem. Transport. Res. Part D (2016), http://dx.doi.org/10.1016/j.trd.2016.09.013

$[s^k, e^k]$, width, $\phi_k$, and water depth, $\alpha_k^h$, which depends on the time step, $h \in H$. The objective of the WSSP is to determine a feasible schedule for the ships that have to access/depart a port through the waterways in such a way that the waiting time of the ships after their arrival is minimized and, therefore, the total time required for the ships to pass through the waterways is minimized. At this point it should be stressed that the incoming and outgoing traffic along the waterways can be simultaneous provided that the model constraints are satisfied. The assumptions of this problem are described as follows:

(a) Each ship $i \in V_1 \cup V_2$ can be scheduled only after its arrival time $ETA_i$ and it has to be scheduled and gone through the waterway until its departure time $ETD_i$.
(b) Each ship $i \in V_1 \cup V_2$ can only be assigned to a waterway $k \in W$ after it becomes available at time $s^k$ and as long as it becomes unavailable at time step $e^k$.
(c) A ship draft, $d_i$ $i \in V_1 \cup V_2$, should be at most the current water depth of its assigned waterway, $\alpha_k^h$ $k \in W, h \in H$.
(d) A subset of incoming and outgoing ships, $V' \subseteq V_1 \cup V_2$, can go through a waterway $k \in W$ simultaneously if the sum of their widths plus appropriate safety distance is not greater than the width of the waterway $k \in W$. That is, $\sum_{i \in V'} w_i \leqslant \phi_k$ if the safety distance is relaxed. (Otherwise, it can also be incorporated into the definition of the $w_i$ data.)

Modelling this problem can borrow ideas from modelling rich vehicle routing problems motivated, *e.g.*, by means of the Multi-Depot Vehicle Routing Problem; see, *e.g.* (Hartl et al., 2006; Golden et al., 2008). In this mathematical model, it is considered that all time measurements are integers. Thus, the planning horizon is divided into discrete time intervals. The input data of the model are summarized as follows:

| | |
|---|---|
| $V$ | Set of $v$ ships |
| $V_1$ | Set of $v_1$ incoming ships |
| $V_2$ | Set of $v_2$ outgoing ships |
| $W$ | Set of waterways |
| $H$ | Set of time steps |
| $t_{ik}$ | Time required for ship $i \in V$ to go through waterway $k \in W$ |
| $l_i$ | Length of ship $i \in V$ |
| $d_i$ | Draft of ship $i \in V$ |
| $w_i$ | Width of ship $i \in V$ |
| $\alpha_k^h$ | Water depth of waterway $k \in W$ at time step $h \in H$ |
| $\phi_k$ | Width of waterway $k \in W$ |
| $[ETA_i, ETD_i]$ | [earliest, latest] arrival/departure time of ship $i \in V$ |
| $[s^k, e^k]$ | [start, end] of the availability time of waterway $k \in W$ |

The following graphs are defined for each waterway. For each waterway there is one for the entering direction and one for the leaving direction:

- A graph $G^k = (V_1^k, A_1^k)$ is generated $\forall k \in W$, where $V_1^k = V_1 \cup \{o_1(k), d_1(k)\}$, with $o_1(k)$ and $d_1(k)$ being additional vertices representing waterway $k$ and $A_1^k \subseteq V_1^k \times V_1^k$.
- A graph $D^k = (V_2^k, A_2^k)$ is generated $\forall k \in W$, where $V_2^k = V_2 \cup \{o_2(k), d_2(k)\}$, with $o_2(k)$ and $d_2(k)$ being additional vertices representing waterway $k$ and $A_2^k \subseteq V_2^k \times V_2^k$.

The decision variables used in the mathematical formulation are defined as follows:

- $x_{ij}^k \in \{0,1\}, \forall\ k \in W, \forall (i,j) \in A_1^k$, set to 1 if ship $j$ is scheduled directly after ship $i$ in waterway $k$, and 0 otherwise.
- $z_{ij}^k \in \{0,1\}, \forall\ k \in W, \forall (i,j) \in A_2^k$, set to 1 if ship $j$ is scheduled directly after ship $i$ in waterway $k$, and 0 otherwise.
- $y_i^k \in \{0,1\}, \forall\ k \in W, \forall i \in V$, set to 1 if ship $i$ is assigned to waterway $k$, and 0 otherwise.
- $\lambda_i^h \in \{0,1\}, \forall h \in H, \forall i \in V$, set to 1 if ship $i$ is passing through a waterway at time step $h$, and 0 otherwise.
- $\delta_i^{hk} \in \{0,1\}, \forall h \in H, \forall k \in W, \forall i \in V$, set to 1 if ship $i$ is passing through waterway $k$ at time step $h$, and 0 otherwise.
- $T_i^k \geqslant 0$, $\forall k \in W, \forall i \in V$, starting time when ship $i$ is going to pass through waterway $k$.
- $T_{o_1(k)}^k \geqslant 0$, $\forall k \in W, \forall i \in V$, starting operation time of waterway $k$ for incoming ships.
- $T_{d_1(k)}^k \geqslant 0$, $\forall k \in W, \forall i \in V$, ending of operation time of waterway $k$ for incoming ships.
- $T_{o_2(k)}^k \geqslant 0$, $\forall k \in W, \forall i \in V$, starting operation time of waterway $k$ for outgoing ships.
- $T_{d_2(k)}^k \geqslant 0$, $\forall k \in W, \forall i \in V$, ending of operation time of waterway $k$ for outgoing ships.

Then the mathematical formulation for the WSSP is as follows:

$$\text{minimize} \sum_{i \in V} \sum_{k \in W} (T_i^k - ETA_i + t_{ik}) \cdot y_i^k \tag{1}$$

Please cite this article in press as: Lalla-Ruiz, E., et al. The waterway ship scheduling problem. Transport. Res. Part D (2016), http://dx.doi.org/10.1016/j.trd.2016.09.013

$$\sum_{k\in W} y_i^k = 1 \quad \forall i \in V \tag{2}$$

$$\sum_{j\in V_1\cup\{d_1(k)\}} x_{o_1(k)j}^k = 1 \quad \forall k \in W \tag{3}$$

$$\sum_{i\in V_1\cup\{o_1(k)\}} x_{id_1(k)}^k = 1 \quad \forall k \in W \tag{4}$$

$$\sum_{j\in V_1\cup\{d_1(k)\}} x_{ij}^k - \sum_{j\in V_1\cup\{o_1(k)\}} x_{ji}^k = 0 \quad \forall i \in V_1, \quad \forall k \in W \tag{5}$$

$$\sum_{j\in V_1\cup\{d_1(k)\}} x_{ij}^k = y_i^k \quad \forall i \in V_1, \quad \forall k \in W, \tag{6}$$

$$\sum_{j\in V_2\cup\{d_2(k)\}} z_{o_2(k)j}^k = 1 \quad \forall k \in W \tag{7}$$

$$\sum_{i\in V_2\cup\{o_2(k)\}} z_{id_2(k)}^k = 1 \quad \forall k \in W \tag{8}$$

$$\sum_{j\in V_2\cup\{d_2(k)\}} z_{ij}^k - \sum_{j\in V_2\cup\{o_2(k)\}} z_{ji}^k = 0 \quad \forall i \in V_2, \quad \forall k \in W \tag{9}$$

$$\sum_{j\in V_2\cup\{d_2(k)\}} z_{ij}^k = y_i^k \quad \forall i \in V_2, \quad \forall k \in W \tag{10}$$

$$T_i^k + \sum_{w\in W} t_i^w y_i^w - T_j^k \leqslant (1 - x_{ij}^k)M \quad \forall i \in V_1, \quad \forall j \in V_1 \cup \{d_1(k)\}, \quad \forall k \in W \tag{11}$$

$$T_{o_1(k)}^k - T_j^k \leqslant (1 - x_{o_1(k)j}^k)M \quad \forall k \in W, \quad \forall j \in V_1 \tag{12}$$

$$T_i^k + \sum_{w\in W} t_i^w y_i^w - T_j^k \leqslant (1 - z_{ij}^k)M \quad \forall i \in V_2, \quad \forall j \in V_2 \cup \{d_2(k)\}, \quad \forall k \in W \tag{13}$$

$$T_{o_2(k)}^k - T_j^k \leqslant (1 - z_{o_2(k)j}^k)M \quad \forall j \in V_2, \quad \forall k \in W \tag{14}$$

$$ETA_i y_i^k \leqslant T_i^k \quad \forall i \in V, \quad \forall k \in W \tag{15}$$

$$T_i^k \leqslant ETD_i y_i^k \quad \forall i \in V, \quad \forall k \in W, \tag{16}$$

$$s^k \leqslant T_{o_1(k)}^k \quad \forall k \in W \tag{17}$$

$$T_{d_1(k)}^k \leqslant e^k \quad \forall k \in W \tag{18}$$

$$s^k \leqslant T_{o_2(k)}^k \quad \forall k \in W \tag{19}$$

$$T_{d_2(k)}^k \leqslant e^k \quad \forall k \in W \tag{20}$$

$$\sum_{k\in W} T_i^k - h \leqslant (1 - \lambda_i^h)M \quad \forall i \in V, \quad \forall h \in H \tag{21}$$

$$h - \left(\sum_{k\in W} T_i^k + s_i - 1\right) \leqslant (1 - \lambda_i^h)M \quad \forall i \in V, \quad \forall h \in H \tag{22}$$

$$\sum_{h\in H} \lambda_i^h = \sum_{k\in W} t_i^k y_i^k \quad \forall i \in V \tag{23}$$

Please cite this article in press as: Lalla-Ruiz, E., et al. The waterway ship scheduling problem. Transport. Res. Part D (2016), http://dx.doi.org/10.1016/j.trd.2016.09.013

$$\delta_i^{hk} \geqslant \lambda_i^h + y_i^k - 1 \quad \forall i \in V, \quad \forall h \in H \quad \forall k \in W \tag{24}$$

$$\sum_{k \in W} \delta_i^{hk} = \lambda_i^h \quad \forall i \in V, \quad \forall h \in H \tag{25}$$

$$\delta_i^{hk}(\alpha_k^h - d_i) \geqslant 0 \quad \forall i \in V, \quad \forall h \in H, \quad \forall k \in W \tag{26}$$

$$\sum_{i \in V} \delta_i^{hk} w_i \leqslant \phi_k \quad \forall k \in W, \quad \forall h \in H \tag{27}$$

$$x_{ij}^k \in \{0,1\}, \forall k \in W, \quad \forall (i,j) \in A_1^k \tag{28}$$

$$z_{ij}^k \in \{0,1\}, \forall k \in W, \quad \forall (i,j) \in A_2^k \tag{29}$$

$$y_i^k \in \{0,1\}, \forall i \in V, \quad \forall k \in W, \tag{30}$$

$$\lambda_i^h \in \{0,1\}, \forall i \in V, \quad \forall h \in H, \tag{31}$$

$$\delta_i^{hk} \in \{0,1\}, \forall i \in V, \quad \forall h \in H, \quad \forall k \in W, \tag{32}$$

$$T_i^k \geqslant 0, \forall k \in W, \quad \forall i \in V \cup \{o_1(k), d_1(k), o_2(k), d_2(k)\} \tag{33}$$

The objective function (1) minimizes the total time required for the ships to pass through the waterways. Constraints (2) establish that every ship $i \in V$ must be assigned to one and only one waterway $k \in W$. Constraints (3) and (4) define the outgoing and incoming flows to the waterways for entering. Flow conservation for the remaining vertices is ensured by constraints (5). Constraints (6) establish the link between variables $x_{ij}^k$ and $y_i^k$. Constraints (7) and (8) define the outgoing and incoming flows to the waterway for leaving. Flow conservation for the remaining vertices is ensured by constraints (9). Constraints (10) establish the link between variables $z_{ij}^k$ and $y_i^k$. Constraints (11) and (12) ensure the precedence in every sequence of entering ships for each waterway $k \in W$. Constraints (13) and (14) ensure the precedence in every sequence of leaving ships for each waterway $k \in W$. The ships' time windows are defined by the constraints (15) and (16). The waterway time windows are defined by constraints (17)–(20). Constraints (21) and (22) link the variables $\lambda_i^h$ and $T_i^k$. Constraints (23) link the variables $\lambda_i^h$ with the total time required to go through the waterway $t_i^k$. Constraints (24) and (25) link the variables $\lambda_i^h$ and $\delta_i^{hk}$. Constraints (26) ensure that the water depth of the waterways is not surpassed by the ships going through them. Constraints (27) ensure that the width of the waterways is not surpassed by the ships going through them. The definition of the variables is shown in constraints (28)–(33). $M$ represents a sufficiently large constant.

The objective function (1) of this problem is quadratic. It can be linearized by defining some additional constraints and an additional variable $b_{ik} \geqslant 0, \forall k \in W, \forall i \in V$, which is equal to $T_i^k$ if $y_i^k = 1$ and 0 otherwise. The additional constraints are as follows:

$$b_{ik} \leqslant y_i^k M \quad \forall i \in V, \quad \forall k \in W \tag{34}$$

$$\sum_{k \in W} b_{ik} = \sum_{k \in W} T_i^k \quad \forall i \in V \tag{35}$$

where $M$ represents a sufficiently large constant.

Therefore, the linearized MILP formulation for the WSSP is as follows:

$$\text{minimize} \sum_{i \in V} \sum_{k \in W} (b_{ik} - (ETA_i + t_{ik}) \cdot y_i^k) \tag{36}$$

subject to constraints (2)–(35).

Before closing this section we should clarify the complexity status of the WSSP by providing the following theorem:

**Theorem 1.** *The WSSP is $\mathcal{NP}$-hard.*

*The prove that the WSSP is $\mathcal{NP}$-hard is shown by reducing it to an already $\mathcal{NP}$-hard problem. This is done by means of the Multi-Depot Vehicle Routing Problem with Time-Windows (MD-VRPTW,* Cordeau et al., 2001*), which is $\mathcal{NP}$-hard due to the fact that it generalizes the Vehicle Routing Problem with Time-Windows (VRPTW,* Lenstra and Rinnooy Kan, 1981; Solomon, 1987*) and the Multi-Depot Multiple Travelling Salesmen Problem (MD-mTSP,* Yang, 1995*) considering in both cases one vehicle/salesman per depot. For simplicity, let us contemplate a restricted version of the WSSP, termed as r-WSSP, that considers the easiest case of only having incoming vessels (outgoing vessels are not considered), namely, $V_2 = \varnothing$ such that $V = V_1$. Moreover, let us consider the* *restricted scenario allowing a maximum of one vessel passing through the waterway at a time without any dimensional constraints due to width and draft.*

*Once those considerations are depicted, the next step of the demonstration is done by associating the r-WSSP to the MD-VRPTW restricted to one vehicle per depot (i.e., MD-mTSP with time windows). In doing so, the vessels are treated as customers and the waterways as depots only having one vehicle. Each vehicle and its respective route represents the passing order through the waterways in r-WSSP. Hence, assigning a vessel for passing through a waterway finds its direct transformation to a vehicle departing from that depot/waterway and visiting that customer/vessel. By means of a toy example of r-WSSP with two vessels* $v_1$ *and* $v_2$ *and one waterway termed as* $w_1$*, a feasible solution* $S = (v_1, v_2)$ *representing the passing order starting with vessel* $v_1$ *and later* $v_2$ *is translated to a MD-VRPTW solution* $S = (d_1, v_1, v_2, d_1)$*, where in this case the depot* $d_1$ *represents the waterway* $w_1$ *in r-WSSP.*

*As can be noticed, we have a multi-graph* $G^k = (V^k, A^k)$ *for each depot/waterway* $k \in W$ *with an origin and destination node such that the set of vertices* $V^k$ *is composed by the customers/vessels and those nodes aforementioned, i.e.,* $V^k = N \cup \{o(k), d(k)\}$ *and travelling times are defined by the arcs* $A^k \subseteq V^k \times V^k$*. Moreover, assuming the same constraints as in MD-mTSP and MD-VRPTW regarding that all the customers have to be visited and also considering that each node in the graph has the problem specific time-window constraints imposed, then the r-WSSP can be transformed into a MD-mTSP with time windows or MD-VRPTW with one vehicle per depot. In this context, it is easy to check that either the MD-mTSP with time windows or the MD-VRPTW have a solution in* $G^k = (V^k, E^k)$ *iff r-WSSP has a solution. Therefore, since MD-mTSP and MD-VRPTW are* $\mathcal{NP}$*-hard then r-WSSP is also* $\mathcal{NP}$*-hard. Finally, including width and draft constraints as well as outgoing vessels generalizes the r-WSSP, thus, we can conclude that WSSP is* $\mathcal{NP}$*-hard.* □

## 4. Solution methods for the WSSP

The use of a general purpose solver such as CPLEX may require large amounts of computational time for solving the WSSP. In this sense, since the WSSP is a real-world daily problem at Shanghai port, it is required to be solved frequently due to operational circumstances such as vessels requiring to enter before their ETA, vessel delays, and change of time windows. Thus, heuristic algorithms that provide high-quality solutions in terms of objective function value in reasonable computational times are required. To address this, we propose, on the one hand, three greedy heuristics where two of them are based on common rule policies. In this regard, assessing their performance allows to contextualize the improvement and contribution that other sophisticated techniques may provide in terms of the reduction of the vessels' waiting time and, thus, enhancement of the terminal quality of service, competitiveness, and environmental care. On the other hand, a simulated annealing approach that takes advantage of the heuristic solutions for yielding better quality solutions is proposed.

### *4.1. Greedy heuristics*

In the context of the WSSP, a solution $S$ is defined as a set of 3-tuples $(\tilde{v}, \tilde{w}, \tilde{h}), \tilde{v} \in N, \tilde{w} \in W, \tilde{h} \in H$, where each represents that a vessel $\tilde{v}$ is assigned to waterway $\tilde{w}$ and its starting time for passing through the waterway is scheduled at time step $\tilde{h}$. Moreover, $S$ is composed of $S_{in}$ and $S_{out}$, where $S = S_{in} \cup S_{out}$; $S_{in}$ corresponds to the incoming ships while $S_{out}$ corresponds to the outgoing ones.

In order to determine the vessels' waterway assignment and schedule, firstly, two sequences of entrance order, $R_{in}$ and $R_{out}$, for the incoming and outgoing ships, respectively, are generated. In this regard, at container terminals, there are some queuing rules used when scheduling incoming vessels. Thus, $R_{in}$ and $R_{out}$ are determined by sorting the ships using specific rules. Some examples are described as follows:

- *Random*. The permutations of both, incoming and outgoing ships, are generated at random. The rationale behind this is to include those situations where container terminal operators may determine the entrance order to the waterways dynamically without a specific strategy.
- *First-Come-First-Served (FCFS)*. This is a common rule used at some container terminals (see Cordeau et al., 2005; Douma et al., 2011; Du et al., 2015; Lalla-Ruiz and Voß, 2016; Liang et al., 2009; Lorenzoni et al., 2006). It is based on establishing the priority of the ships according to their arrival time. That is, the earliest vessel to arrive to the waiting area for accessing the waterways is the first to be allowed to pass through one of them.
- *Shortest Time Windows length (STW)*. The vessels are sorted considering the length of vessel time windows. In this case, vessels with the narrowest time windows will pass through the waterway first. The basis of this strategy is to establish a priority for those ships integrated in shipping routes requiring narrow time windows to satisfy the different route time windows.

The previous rules allow to obtain a permutation of the incoming and outgoing container vessels for passing through the waterways. There are, then, three heuristics that can be obtained by using these rules in such a way that the ships are iteratively assigned to the best possible waterway by means of the objective function value, namely, the waterway is selected for each ship by minimizing the impact on the objective function value.

Please cite this article in press as: Lalla-Ruiz, E., et al. The waterway ship scheduling problem. Transport. Res. Part D (2016), http://dx.doi.org/10.1016/j.trd.2016.09.013

**Algorithm 1.** Waterway Assignment Algorithm

```
1: $S \leftarrow \varnothing$
2: $f_{obj}(S) = 0$
3: $R_{in} \leftarrow$ Create a sorted sequence of incoming vessels according to selected rule
4: $R_{out} \leftarrow$ Create a sorted sequence of outgoing vessels according to selected rule
5: $count_{in} \leftarrow 1$
6: $count_{out} \leftarrow 1$
7: while $(count_{in} + count_{out} < |V|)$ do
8:   if $(count_{in} \leqslant |V_1|)$ then
9:     $v_{in} \leftarrow$ Select vessel $R_{in}(count_{in})$
10:    $w_{in} \leftarrow$ Select waterway and time $h_{in}$ for vessel $v_{in}$ that allows the minimum impact on $f_{obj}(S)$
11:    Assign $v_{in}$ to $w_{in}$ in $S$
12:    if (incoming vessel is assigned) then
13:      $count_{in} \leftarrow count_{in} + 1$
14:    else
15:      Return $-1$
16:    end if
17:  end if
18:  if $(count_{out} \leqslant |V_2|)$ then
19:    $v_{out} \leftarrow$ Select vessel $R_{out}(count_{out})$
20:    $w_{out} \leftarrow$ Select waterway and time $h_{out}$ for vessel $v_{out}$ that allows the minimum impact on $f_{obj}(S)$
21:    Assign $v_{out}$ to $w_{out}$ in $S$
22:    if (outgoing vessel is assigned) then
23:      $count_{out} \leftarrow count_{out} + 1$
24:    else
25:      Return $-1$
26:    end if
27:  end if
28: end while
29: Return S
```

As indicated in Algorithm 1, the initial solution, $S$, is empty (line 1). Its associated objective function value, $f_{obj}(S)$, is set to 0 (line 2). Once this initialization is done, depending on the given rule, a permutation of incoming and outgoing ships $R_{in}$ and $R_{out}$, respectively, is generated (lines 3–4). For example, using the FCFS rule, the first element of the incoming vessels permutation, $R_{in}(1)$, is the first incoming ship that arrives to the waterway entrance, and will be the first incoming ship to be scheduled. With the permutation already defined, the incoming and outgoing ships are assigned one at a time to the best possible waterway following the order given by the sorted list (lines 8–17; lines 18–27). The best possible waterway is determined according to the impact on the objective function value of the solution (line 10 for incoming vessels; line 20 for outgoing vessels). That is, each vessel is assigned to the waterway that least increases the objective function value of the solution built until that moment. It should be noted that for assigning a ship to a waterway the dimensional constraints (draft, width) as well as time-window constraints have to be satisfied (line 12 and line 22). Otherwise, the solution is considered infeasible (line 15; line 25).

Depending on the rule used in Algorithm 1, different heuristics can be developed. In this regard, the names of the heuristics in this work are derived from the names of the rules, *i.e.*, *Random Greedy* (Random-G), *First-Come First-Served Greedy* (FCFS-G), and *Shortest Time Windows length Greedy* (STW-G).

### 4.2. Simulated annealing

Simulated Annealing (SA, Kirkpatrick et al., 1983) is a popular local search meta-heuristic that extends the basic local search by allowing movements to inferior solutions in terms of objective function value (Voß, 2001). It has been successfully applied to seaside maritime logistic problems (Bierwirth and Meisel, 2015); in ship routing some examples from Kosmas and Vlachos (2012), Dowsland et al. (2007) motivate the development of a SA as a solution method for this problem. Moreover, the selection of this approach is also justified by the desire to avoid getting trapped by poor local optima by allowing worsening moves as well as having a fast computational performance (as highlighted in Section 5). In a basic SA algorithm a candidate move is randomly selected; if it leads to a better solution than the current one, the move is accepted. In case the move does not lead to an improvement of the objective function value, it may be accepted according to a probability that depends on the deterioration $\Delta$ of the objective function value. The probability of acceptance is computed as $e^{-\Delta/T}$, using the temperature $T$ as a control parameter.

Please cite this article in press as: Lalla-Ruiz, E., et al. The waterway ship scheduling problem. Transport. Res. Part D (2016), http://dx.doi.org/10.1016/j.trd.2016.09.013

For solving this problem, we propose a SA approach that uses the different heuristics outlined in the previous subsection. In Algorithm 2, the pseudocode of SA is shown. The initial solution is generated (line 1) by using one of the heuristics proposed (*i.e.*, Random-G, FCFS-G, and STW-G). A solution neighbour, $S'$, is randomly generated using a swap move (*i.e.*, two incoming and outgoing vessels exchange their positions in their respective sequences). For each temperature, $R$ iterations are executed. After running $R$ iterations, $T$ is decreased $T \leftarrow T \cdot \gamma$, where $0 < \gamma < 1$. Additionally, the number of iterations $R$ used at each temperature is updated, $R \leftarrow R \cdot \beta$, with $0 < \beta < 1$. The complete SA algorithm is executed until the temperature reaches a certain threshold, $T_{min}$.

**Algorithm 2.** Simulated Annealing for the WSSP

```
Require: $T, T_{min}, R, \beta, \gamma$
 1: $S \leftarrow$ generate a initial solution using heuristic (see Section 4.1)
 2: while ($T_{min} < T$) do
 3:   for ($t \leftarrow 1$ to $R$) do
 4:     Generate a solution $S' \in N(S)$
 5:     Calculate $\Delta_{S,S'} = f_{obj}(S') - f_{obj}(S)$
 6:     if ($\Delta_{S,S'} \leqslant 0$) then
 7:       $S \leftarrow S'$
 8:     else
 9:       $S \leftarrow S'$ with probability $e^{-\Delta/T}$
10:     end if
11:   end for
12:   $T = T \cdot \gamma$
13:   $R = R \cdot \beta$
14: end while
15: Return S
```

**2-opt neighbourhood structure**: The neighbourhood structure used in this work is based on 2-opt moves. That is, given a solution, $S$, the *2-opt* neighbourhood, $N(S)$, is composed of the neighbourhood $N(S_{in})$ obtained by swapping two incoming vessels, and $N(S_{out})$ obtained by swapping two outgoing vessels in such a way, that $N(S) = N(S_{in}) \cup N(S_{out})$, where $N(S_{in}) = \{S_{in} \circ (i,j) : 1 \leqslant i,j \leqslant V_{in}, i \neq j\}$ and $N(S_{out}) = \{S_{out} \circ (i,j) : 1 \leqslant i,j \leqslant V_{in}, i \neq j\}$.

## 5. Computational experiments

This section is devoted to present the computational experiments carried out to validate our model and assess the performance of the proposed heuristics. In doing so, a benchmark suite is proposed. The mathematical model has been implemented in CPLEX with a time limit of 3600 s. The solution approaches and the mathematical model were executed on a computer equipped with an Intel i7 3.5 GHz and 16 GB of RAM. For the simulated annealing, by preliminary experiments, we identified the following parameters: $T = 100, T_{min} = 1, R = 10, \gamma = 0.9$, and $\beta = 0.9$.

### *5.1. Problem generation*

In order to evaluate the performance of the proposed model (implemented in CPLEX) and the heuristics proposed in this work, a benchmark suite is proposed. These problem instances are based on data provided by the port of Shanghai (China). In this regard, besides the geographic information, for generating this benchmark suite, we had access to historical data related to the shipping traffic and the tidal measures at the Estuary provided by the Waigaoqiao terminal. Furthermore, since this problem can be translated to other scenarios, we have generated problem instances of different sizes. Hence, according to the information provided, we fix the parameters for each case according to the minimum and maximum draft, length and breadth of the vessels and randomly generate the information of the vessels following a discrete uniform distribution. Moreover, as indicated above, we had to take into account data from the minimum and maximum tide levels of the waterways provided by terminal managers. In the following, we list the set of instances generated for assessing the WSSP.

- $|V| = 30$ vessels ($|V_1| = 15; |V_2| = 15$) within $|W| = 2$ waterways
- $|V| = 30$ vessels ($|V_1| = 20; |V_2| = 20$) within $|W| = 4$ waterways
- $|V| = 40$ vessels ($|V_1| = 20; |V_2| = 20$) within $|W| = 2$ waterways
- $|V| = 40$ vessels ($|V_1| = 20; |V_2| = 20$) within $|W| = 4$ waterways
- $|V| = 50$ vessels ($|V_1| = 25; |V_2| = 25$) within $|W| = 2$ waterways
- $|V| = 50$ vessels ($|V_1| = 25; |V_2| = 25$) within $|W| = 4$ waterways
- $|V| = 60$ vessels ($|V_1| = 30; |V_2| = 30$) within $|W| = 2$ waterways
- $|V| = 60$ vessels ($|V_1| = 30; |V_2| = 30$) within $|W| = 4$ waterways

Please cite this article in press as: Lalla-Ruiz, E., et al. The waterway ship scheduling problem. Transport. Res. Part D (2016), http://dx.doi.org/10.1016/j.trd.2016.09.013

Five problem instances of each set have been generated, thus, a total of 40 problem instances. Since this is a daily problem, we have set a planning horizon of one day divided into 48 time steps.

**Yangtze scenario – additional considerations**: Furthermore, although the mathematical model can be used in scenarios that allow more than two ships to pass through a waterway at the same time, in this work we address the particular scenario at the Yangtze Estuary where -according to practitioners- some assumptions regarding its geographic situation have to be used when generating the set of instances:

1. A ship, $i \in V$ with $l_i > 275$ m, cannot access the port through the waterways within the night time windows $[t, t']$.
2. A ship, $i \in V$ with $l_i > 150$ m, has its draft increased 1 m for the sake of safety.
3. A maximum of two ships can go through the waterway in the same time step.

It should be noted that considerations depicted in points 1 and 2 are taken into account when generating the problem instances. Nevertheless, for the consideration described in point 3, we have to include the following constraints to the mathematical model:

$$\sum_{i \in V_1} \delta_i^{hk} \leqslant 1 \quad \forall k \in W, \quad \forall h \in H \tag{37}$$

$$\sum_{i \in V_2} \delta_i^{hk} \leqslant 1 \quad \forall k \in W, \quad \forall h \in H \tag{38}$$

Constraints (37) and (38) do not allow that more than one ship goes through the waterway at the same time step and type of incoming or outgoing vessels.

### 5.2. Comparison among heuristics

In order to assess the performance of the heuristics proposed in this work (Random-G, FCFS-G, and STW-G), a comparison of their behaviour in terms of objective function value is presented in this subsection.

Tables 1 and 2 illustrate the results provided by the greedy heuristics for a representative set of instances proposed in this work. The algorithms have been run ten times. For Random-G, the worst (Max), average (Avg), and best (Min) objective function values are reported. It should be noted that FCFS-G and STW-G are deterministic, hence, they provide the same solution regardless the number of repetitions. Since the computational times required by the algorithms are very small (about 0.001 s) they have not been included in the tables.

In the tables, it can be checked that FCFS-G and STW-G are not able to provide a solution in some cases. On the other hand, Random-G may not be able to provide a solution in some cases, hence, taking advantage of the tiny time effort required at each run, Random-G is executed until a solution is provided. Furthermore, the cases where FCFS-G and STW-G are not able to provide a solution belong to those problem instance sets that establish two waterways. This makes sense since there are several real constraints that have to be taken into account such as short length time windows, vessel drafts and widths, vessel transit time, and large number of vessels. Additionally, these results indicate that for common strategies as the ones proposed in this work, the instances become difficult when there are less waterways in terms of providing feasible solutions.

At the light of these results, the use of Random-G is advisable in practical scenarios instead of using FCFS-G and STW-G since it provides a feasible solution in all the cases. In this sense, as indicated in some works (see Cordeau et al., 2005; Liang et al., 2009; Lorenzoni et al., 2006; Douma et al., 2011; Kontovas and Psaraftis, 2011) the FCFS policy is commonly used at some container terminals when scheduling vessels. In this case, the use of these strategies would not be successful when addressing some instances due to the fact that they are not able to provide a feasible solution. Thus, their use may require that terminal managers or DSS using these rules need to consider soft time windows or require that some vessels wait to the next day to pass through the waterway to access the terminal.

### 5.3. Mathematical programming and metaheuristics results and discussion

In this subsection, we present the comparison among the MILP mathematical model implemented in CPLEX, and the proposed SA approach using as initialization the algorithms proposed in this work:

1. Simulated Annealing using Random-G as initialization method ($SA_{RG}$)
2. Simulated Annealing using FCFS-G as initialization method ($SA_{FCFS-G}$)
3. Simulated Annealing using STW-G as initialization method ($SA_{STW-G}$)

Moreover, a comparison among SA approaches and the common queue rules used for scheduling in order to evaluate the benefit of using SA is also presented.

Please cite this article in press as: Lalla-Ruiz, E., et al. The waterway ship scheduling problem. Transport. Res. Part D (2016), http://dx.doi.org/10.1016/j.trd.2016.09.013

**Table 1**
Comparison among heuristics for the WSSP for a representative set of instances with two waterways.

| Instances | | | | | Random-G | | | FCFS-G | STW-G |
|---|---|---|---|---|---|---|---|---|---|
| $\|V\|$ | $\|W\|$ | $\|V_1\|$ | $\|V_2\|$ | id | Min | Avg | Max | | |
| 30 | 2 | 15 | 15 | 1 | 169 | 186.40 | 210 | 151 | 189 |
| | | | | 2 | 97 | 108.70 | 127 | 88 | 106 |
| 40 | 2 | 20 | 20 | 1 | 280 | 307.90 | 344 | – | – |
| | | | | 2 | 177 | 189.60 | 205 | 184 | 192 |
| 50 | 2 | 25 | 25 | 1 | 183 | 213.40 | 222 | – | – |
| | | | | 2 | 135 | 154.20 | 167 | 155 | 150 |
| 60 | 2 | 30 | 30 | 1 | 245 | 273.70 | 319 | 252 | 318 |
| | | | | 2 | 484 | 546.40 | 580 | – | – |

**Table 2**
Comparison among heuristics for the WSSP for a representative set of instances with four waterways.

| Instances | | | | | Random-G | | | FCFS-G | STW-G |
|---|---|---|---|---|---|---|---|---|---|
| $\|V\|$ | $\|W\|$ | $\|V_1\|$ | $\|V_2\|$ | id | Min | Avg | Max | | |
| 30 | 4 | 15 | 15 | 1 | 41 | 42.60 | 44 | 44 | 43 |
| | | | | 2 | 85 | 97.10 | 117 | 87 | 106 |
| 40 | 4 | 20 | 20 | 1 | 113 | 119.10 | 126 | 113 | 116 |
| | | | | 2 | 108 | 109.70 | 114 | 104 | 114 |
| 50 | 4 | 25 | 25 | 1 | 110 | 116.20 | 123 | 116 | 115 |
| | | | | 2 | 85 | 90.00 | 96 | 96 | 85 |
| 60 | 4 | 30 | 30 | 1 | 93 | 105.40 | 121 | 93 | 120 |
| | | | | 2 | 134 | 151.50 | 171 | 139 | 148 |

Tables 3–6 report the computational results provided by CPLEX in terms of upper bound (UB), lower bound (LB), relative error (Gap(%)) and computational time (time (s)). For the SA approaches, the best objective function value (Obj.), the relative error (Gap(%)), and the average computational time (time (s)) are reported.

The results shown in Table 3 indicate that for the instances of $|W| = 4$ CPLEX, $SA_{RG}$, and $SA_{STW-G}$ exhibit a similar performance in terms of objective function value. In this regard, SA using FCFS-G as initialization method is not able to reach a solution. Furthermore, in those instances where CPLEX is able to solve them to optimality (30×4-4 and 30×4-5), SA requires far less computational time regardless the initialization method. From Tables 4–6, it can be noted that CPLEX is not able to provide a solution for some instances, especially, in the set of instances considering 60 vessels. This also happens less often for $SA_{FCFS-G}$. Furthermore, it should be noted that $SA_{RG}$ and $SA_{STW-G}$ exhibit a similar performance. In this sense, $SA_{STW-G}$ presents a slightly better performance on average in terms of objective function value. Regarding the computational times, the proposed SA algorithms require, on average, less than 0.35 s to provide a feasible solution.

$SA_{RG}$ and $SA_{STW}$ (see Tables 3–6) present a similar performance. Hence, in order to evaluate more in depth both approaches by means of the best, average and worst value within 10 runs, Tables 7 and 8 report a detailed comparison. Moreover, since common queue strategies such as FCFS are used at some terminals, the relative error based on FCFS-G (Gap$_{FCFS}$(%)) and STW-G (Gap$_{STW}$(%)) are calculated with respect to the average values provided by $SA_{RG}$ and $SA_{STW}$. The rationale behind this is to make a fair comparison with respect to FCFS-G and STW-G, given that they are deterministic algorithms and, consequently, provide always the same objective value on average.

Besides $SA_{RG}$ and $SA_{STW}$ show a similar performance, on average, in terms of the best solutions provided for the smallest instances (see Table 7), it should be noted that when the size of the scenarios increases the quality of the solutions provided by $SA_{STW}$ becomes slightly better (see Table 8). Additionally, $SA_{STW}$ presents a better robustness by means of worst and average objective function values. This characteristic is relevant when this algorithm has to be executed jointly with other algorithms and several executions have to be made. Moreover, $SA_{STW}$ is more competitive from the point of view of shipping companies, the longer the vessels have to wait the more negative the impact will be on their economical benefits since they may have more fuel costs -emitting undesirable emissions- as well as delays in their commercial routes for visiting other terminals. Finally, from the terminal operator's viewpoint, the benefit of using the proposed SA approaches instead of the greedy strategies based on queue policies, would have a positive overall impact in terms of allowing more steady operations, reducing emissions in the fuel saving of the vessels thanks to shorter waiting times, and allowing to serve more vessels influencing an increased competitiveness.

Furthermore, when the SA is contextualized by considering the heuristics using traditional policies, especially with the widely known FCFS policy, SA is able to provide, in the best case, a solution 26.86% better than the one provided by FCFS-G, and 60% better than STW-G within 1 s. Those improvement percentages means reduction of unnecessary vessels' waiting time involving consequently fuel costs, emissions, commercial route timing, etc. In this context, by means of related works, if we consider the entering and leaving to the terminal by waterways as a part of a route, the reduction of the waiting times, as indicated in Fagerholt et al. (2010), increases the potential to reduce fuel consumption and, thus, emissions.

Please cite this article in press as: Lalla-Ruiz, E., et al. The waterway ship scheduling problem. Transport. Res. Part D (2016), http://dx.doi.org/10.1016/j.trd.2016.09.013

**Table 3**
Comparison among CPLEX, SA with Random-G ($SA_{RG}$), SA with FCFS-G ($SA_{FCFS-G}$), and SA with STW-G ($SA_{STW-G}$) for problem instances of 30 vessels.

| Instances | | | | | CPLEX | | | | $SA_{RG}$ | | | $SA_{FCFS-G}$ | | | $SA_{STW-G}$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\|V\|$ | $\|W\|$ | $\|V_1\|$ | $\|V_2\|$ | id | UB | LB | Gap (%) | Time (s) | Obj. | Gap (%) | Time (s) | Obj. | Gap (%) | Time (s) | Obj. | Gap (%) | Time (s) |
| 30 | 2 | 15 | 15 | 1 | 205 | 91.89 | 55.17 | 3600 | 139 | 33.89 | 0.06 | 139 | 33.89 | 0.06 | 139 | 33.89 | 0.06 |
| | | | | 2 | 157 | 57.12 | 63.62 | 3600 | 85 | 32.80 | 0.05 | 85 | 32.80 | 0.05 | 85 | 32.80 | 0.05 |
| | | | | 3 | 128 | 71.00 | 44.53 | 3600 | 91 | 21.98 | 0.05 | 91 | 21.98 | 0.05 | 91 | 21.98 | 0.05 |
| | | | | 4 | 196 | 66.00 | 66.33 | 3600 | 120 | 45.00 | 0.05 | 120 | 45.00 | 0.05 | 120 | 45.00 | 0.05 |
| | | | | 5 | 46 | 41.00 | 10.87 | 3600 | 46 | 10.87 | 0.04 | 46 | 10.87 | 0.04 | 46 | 10.87 | 0.04 |
| 30 | 4 | 15 | 15 | 1 | 41 | 33.73 | 17.73 | 3600 | 41 | 17.73 | 0.08 | – | – | 0.08 | 41 | 17.73 | 0.08 |
| | | | | 2 | 78 | 74.56 | 4.41 | 3600 | 78 | 4.41 | 0.13 | 78 | 4.41 | 0.13 | 78 | 4.41 | 0.13 |
| | | | | 3 | 42 | 38.07 | 9.36 | 3600 | 42 | 9.36 | 0.13 | 42 | 9.36 | 0.12 | 42 | 9.36 | 0.13 |
| | | | | 4 | 76 | 76.00 | 0.00 | 759.57 | 76 | 0.00 | 0.11 | 76 | 0.00 | 0.11 | 76 | 0.00 | 0.11 |
| | | | | 5 | 67 | 67.00 | 0.00 | 504.9 | 67 | 0.00 | 0.13 | 67 | 0.00 | 0.14 | 67 | 0.00 | 0.12 |
| | | | | | | | | | 78.50 | 17.60 | 0.08 | – | – | 0.08 | 78.50 | 17.60 | 0.08 |

**Table 4**
Comparison among CPLEX, SA with Random-G ($SA_{RG}$), SA with FCFS-G ($SA_{FCFS-G}$), and SA with STW-G ($SA_{STW-G}$) for problem instances of 40 vessels.

| Instance | | | | | CPLEX | | | | $SA_{RG}$ | | | $SA_{FCFS-G}$ | | | $SA_{STW-G}$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\|V\|$ | $\|W\|$ | $\|V_1\|$ | $\|V_2\|$ | id | UB | LB | Gap (%) | Time (s) | Obj. | Gap (%) | Time (s) | Obj. | Gap (%) | Time (s) | Obj. | Gap (%) | Time (s) |
| 40 | 2 | 20 | 20 | 1 | – | 108.30 | – | 3600 | 227 | 52.29 | 0.09 | – | – | 0.49 | 225 | 51.87 | 0.08 |
| | | | | 2 | 237 | 88.21 | 62.78 | 3600 | 149 | 40.80 | 0.08 | 149 | 40.80 | 0.07 | 149 | 40.80 | 0.07 |
| | | | | 3 | – | 97.00 | – | 3600 | 199 | 51.26 | 0.07 | 199 | 51.26 | 0.07 | 199 | 51.26 | 0.06 |
| | | | | 4 | 131 | 58.00 | 55.73 | 3600 | 82 | 29.27 | 0.08 | 82 | 29.27 | 0.08 | 82 | 29.27 | 0.08 |
| | | | | 5 | 161 | 46.00 | 71.43 | 3600 | 81 | 43.21 | 0.10 | 81 | 43.21 | 0.10 | 81 | 43.21 | 0.10 |
| 40 | 4 | 20 | 20 | 1 | 117 | 95.44 | 18.43 | 3600 | 107 | 10.80 | 0.10 | 107 | 10.80 | 0.10 | 107 | 10.80 | 0.10 |
| | | | | 2 | 213 | 98.00 | 53.99 | 3600 | 101 | 2.97 | 0.10 | 101 | 2.97 | 0.10 | 101 | 2.97 | 0.11 |
| | | | | 3 | 75 | 42.00 | 44.00 | 3600 | 70 | 40.00 | 0.13 | 70 | 40.00 | 0.13 | 70 | 40.00 | 0.13 |
| | | | | 4 | 197 | 61.02 | 69.03 | 3600 | 80 | 23.73 | 0.10 | 80 | 23.73 | 0.10 | 80 | 23.73 | 0.10 |
| | | | | 5 | 298 | 168.00 | 43.62 | 3600 | 193 | 12.95 | 0.13 | 193 | 12.95 | 0.16 | 193 | 12.95 | 0.16 |
| | | | | | | | | | 128.90 | 30.73 | 0.10 | – | – | 0.14 | 128.70 | 30.69 | 0.10 |

**Table 5**
Comparison among CPLEX, SA with Random-G ($SA_{RG}$), SA with FCFS-G ($SA_{FCFS-G}$), and SA with STW-G ($SA_{STW-G}$) for problem instances of 50 vessels.

| Instances | | | | | CPLEX | | | | $SA_{RG}$ | | | $SA_{FCFS-G}$ | | | $SA_{STW-G}$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\|V\|$ | $\|W\|$ | $\|V_1\|$ | $\|V_2\|$ | id | UB | LB | Gap (%) | Time (s) | Obj. | Gap (%) | Time (s) | Obj. | Gap (%) | Time (s) | Obj. | Gap (%) | Time (s) |
| 50 | 2 | 25 | 25 | 1 | 179 | 110.54 | 38.25 | 3600 | 172 | 35.73 | 0.07 | 172 | 35.73 | 0.08 | 172 | 35.73 | 0.08 |
| | | | | 2 | 113 | 72.00 | 36.28 | 3600 | 108 | 33.33 | 0.11 | 108 | 33.33 | 0.11 | 108 | 33.33 | 0.11 |
| | | | | 3 | – | 104.69 | – | 3600 | 242 | 56.74 | 0.06 | 242 | 56.74 | 0.07 | 241 | 56.56 | 0.07 |
| | | | | 4 | – | 120.00 | – | 3600 | 324 | 62.96 | 0.07 | 324 | 62.96 | 0.08 | 325 | 63.08 | 0.08 |
| | | | | 5 | 105 | 69.02 | 34.26 | 3600 | 100 | 30.98 | 0.12 | 100 | 30.98 | 0.12 | 100 | 30.98 | 0.13 |
| 50 | 4 | 25 | 25 | 1 | 106 | 82.00 | 22.64 | 3600 | 100 | 18.00 | 0.16 | 100 | 18.00 | 0.17 | 100 | 18.00 | 0.16 |
| | | | | 2 | 258 | 74.00 | 71.32 | 3600 | 82 | 9.76 | 0.10 | 82 | 9.76 | 0.10 | 82 | 9.76 | 0.10 |
| | | | | 3 | 117 | 98.00 | 16.34 | 3600 | 107 | 8.41 | 0.16 | 107 | 8.41 | 0.17 | 107 | 8.41 | 0.17 |
| | | | | 4 | 241 | 70.00 | 70.95 | 3600 | 82 | 14.63 | 0.17 | 82 | 14.63 | 0.17 | 82 | 14.63 | 0.19 |
| | | | | 5 | 79 | 62.00 | 21.52 | 3600 | 78 | 20.51 | 0.26 | 78 | 20.51 | 0.25 | 78 | 20.51 | 0.25 |
| | | | | | | | | | 139.50 | 29.11 | 0.13 | 139.50 | 29.11 | 0.13 | 139.50 | 29.10 | 0.13 |

Additionally, Moon and Woo (2014) indicate that the improvement of efficiency in port operations enhance the operational efficiency of ships by reducing operation costs and $CO_2$ emission. The above, therefore, supports and points out the benefit that the use of SA has not only in the cost reductions but also in reduction of emissions and shipping companies satisfaction.

In Fig. 4 we illustrate the advantage of $SA_{STW}$ over $SA_{RG}$ by means of objective function value. As can be checked, in all cases $SA_{STW}$ provides at least, on average, the same quality solutions than $SA_{RG}$. This provides the insight, that although STW-G is not always able to provide a solution on its own but Random-G, within the SA approach provided in this work STW-G is able to exhibit a very competitive performance by means of best, average and worst solutions. On the other hand, $SA_{FCFS-G}$ is not included in the figure, since it does not provide a feasible solution in some cases, which indicates that under this strategy

**Table 6**
Comparison among CPLEX, SA with Random-G ($SA_{RG}$), SA with FCFS-G ($SA_{FCFS-G}$), and SA with STW-G ($SA_{STW-G}$) for problem instances of 60 vessels.

| Instances | | | | | CPLEX | | | | $SA_{RG}$ | | | $SA_{FCFS-G}$ | | | $SA_{STW-G}$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\|V\|$ | $\|W\|$ | $\|V_1\|$ | $\|V_2\|$ | id | UB | LB | Gap (%) | Time (s) | Obj. | Gap (%) | Time (s) | Obj. | Gap (%) | Time (s) | Obj. | Gap (%) | Time (s) |
| 60 | 2 | 30 | 30 | 1 | – | 78 | – | 3600 | 239 | 67.36 | 0.10 | – | – | 0.42 | 237 | 67.09 | 0.10 |
| | | | | 2 | – | 139.7 | – | 3600 | 199 | 29.80 | 0.10 | 199 | 29.80 | 0.09 | 198 | 29.44 | 0.10 |
| | | | | 3 | – | 90.7 | – | 3600 | 520 | 82.56 | 0.10 | – | – | 0.66 | 443 | 79.53 | 0.10 |
| | | | | 4 | – | 92.27 | – | 3600 | 326 | 71.70 | 0.10 | – | – | 0.87 | 290 | 68.18 | 0.12 |
| | | | | 5 | – | 201.06 | – | 3600 | 266 | 24.41 | 0.10 | 262 | 23.26 | 0.11 | 262 | 23.26 | 0.11 |
| 60 | 4 | 30 | 30 | 1 | 180 | 67 | 62.78 | 3600 | 75 | 10.67 | 0.34 | 75 | 10.67 | 0.33 | 75 | 10.67 | 0.33 |
| | | | | 2 | – | 70 | – | 3600 | 115 | 39.13 | 0.32 | 115 | 39.13 | 0.32 | 115 | 39.13 | 0.32 |
| | | | | 3 | 86 | 73 | 15.12 | 3600 | 83 | 12.05 | 0.19 | 83 | 12.05 | 0.19 | 83 | 12.05 | 0.20 |
| | | | | 4 | – | 141 | 141.00 | 3600 | 187 | 24.60 | 0.24 | 187 | 24.60 | 0.23 | 188 | 25.00 | 0.24 |
| | | | | 5 | – | 83 | – | 3600 | 106 | 21.70 | 0.25 | 106 | 21.70 | 0.24 | 106 | 21.70 | 0.25 |
| | | | | | | | | | 211.60 | 38.40 | 0.18 | – | – | 0.35 | 199.70 | 37.60 | 0.19 |

some ships are not able to be scheduled to pass through the 1-day time horizon. This feature is important since, as indicated before, this is a common rule used at some container terminals.

## 6. Conclusions and further research

In this work, we have presented the Waterway Ship Scheduling Problem (WSSP) aimed at scheduling the traffic of ships along waterways. At the light of the analysis and results provided, we found that solving this problem may lead to win-win solutions since reducing ships' waiting time yields to economic, operational, and environmental savings for both, container terminals and shipping companies. In order to solve this problem we have developed a MILP mathematical formulation and implemented it on a general purpose solver such as CPLEX. Moreover, since the formulation is not able to provide a feasible solution within reasonable time limits for some scenarios, some greedy heuristics based on commonly used queue rules as well as a simulated annealing (SA) algorithm are proposed. In order to assess their performance, a benchmark suite which considers some real-issues from the Yangtze Estuary has been considered.

From the computational experiments carried out in this paper it can be concluded that the problem is difficult for being solved even for small-sized problem instances using a general purpose solver. Nevertheless, the SA approaches proposed in this work are able to provide high-quality solutions in short computational times. The experimental tests also show that the SA approaches are adaptable for practical-size problems used nowadays. In this regard, it can be highlighted that the computational effort required by them is not strongly influenced by the dimensions of the instances since they provide feasible solutions with a similar computational effort for different size instances. This characteristic makes SA worthy for practical cases where, on one hand, the number of ships may vary due to delays or changes in shipping routes and, on the other hand, the number of waterways where ships are allowed to pass through can change depending on how they are planned or intended to be used by the terminal(s). On the other hand, the comparison of SA with common queue policies used at container terminals show that a relevant improvement can be obtained in terms of reducing the unnecessary ships' waiting time. This allows a more fluid ship traffic yielding to economical and strategic benefits as well as an increase in the quality of the environmental care level through the reduction of vessels' emissions. Moreover, the computational results allow to indicate, from the perspective of container terminals, that the improvement in the management of the traffic along the waterways results not only in an enhancement of terminal's competitiveness but also in reducing costs and emissions of the shipping lines by reducing their waiting time allowing a smooth routing. On the other hand, not considering the dimensional and tidal constraints may lead to wrong ETAs and ETDs as well as longer waiting times for ships in order to access the waterways. All this is apart from mentioning the time savings for the ship schedule controllers of SIPG since they have to check all the reported ships and modify their related, eventually inappropriate schedule.

Furthermore, besides the potential benefits of applying these solution approaches to real cases, these approaches can also be used as a suitable tool in the negotiation between the terminal operators and the shipping companies while schedules are being agreed. The terminal operators would be able to get a perspective of how the range of possible schedules would affect the rest of the vessels' schedules while the negotiations are being achieved. In this respect, the use of exact techniques, as can be seen from the computational results using CPLEX, requires a high computational effort in terms of execution time which would cause a delay or slow-down in the decision-making process during the negotiations between the terminal operators and the shipping companies. Hence, the use of approximate techniques as the ones proposed in this work is then appropriate for quickly getting all the possible schedules that the terminal could hold and offer to the shipping companies without compromising its performance or the contracts already agreed upon.

Considering the contributions presented in this paper, the next stage of our research will be focused on the analysis of how the consideration of the tide impacts the waiting times of the vessels. Another open line for future research is to integrate this approach to other related operations taking place at container terminals such as berth scheduling and quay crane

Please cite this article in press as: Lalla-Ruiz, E., et al. The waterway ship scheduling problem. Transport. Res. Part D (2016), http://dx.doi.org/10.1016/j.trd.2016.09.013

**Table 7**

Comparison of $SA_{RG}$ and $SA_{STW}$ for the problem instances of 30 and 40 vessels. The benefits of using Simulated Annealing instead of algorithms based on queue rules (FCFS-G and STW-G) are shown.

| Instances | | | | | FCFS-G | STW-G | $SA_{RG}$ | | | | | $SA_{STW}$ | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\|V\|$ | $\|W\|$ | $\|V_1\|$ | $\|V_2\|$ | id | | | Min | Avg | Max | $Gap_{FCFS}$(%) | $Gap_{STW}$(%) | Min | Avg | Max | $Gap_{FCFS}$(%) | $Gap_{STW}$(%) |
| 30 | 2 | 15 | 15 | 1 | 151 | 189 | 139 | 140.00 | 142 | 7.86 | 35.00 | 139 | 139.50 | 141 | 8.24 | 35.48 |
| | | | | 2 | 88 | 106 | 85 | 85.00 | 85 | 3.53 | 24.71 | 85 | 85.30 | 86 | 3.17 | 24.27 |
| | | | | 3 | 93 | 112 | 91 | 91.00 | 91 | 2.20 | 23.08 | 91 | 91.00 | 91 | 2.20 | 23.08 |
| | | | | 4 | 138 | 167 | 120 | 120.50 | 121 | 14.52 | 38.59 | 120 | 120.30 | 121 | 14.71 | 38.82 |
| | | | | 5 | 47 | 49 | 46 | 46.00 | 46 | 2.17 | 6.52 | 46 | 46.00 | 46 | 2.17 | 6.52 |
| 30 | 4 | 15 | 15 | 1 | 44 | 43 | 41 | 41.00 | 41 | 7.32 | 4.88 | 41 | 41.00 | 41 | 7.32 | 4.88 |
| | | | | 2 | 87 | 106 | 78 | 78.00 | 78 | 11.54 | 35.90 | 78 | 78.00 | 78 | 11.54 | 35.90 |
| | | | | 3 | 45 | 45 | 42 | 42.00 | 42 | 7.14 | 7.14 | 42 | 42.00 | 42 | 7.14 | 7.14 |
| | | | | 4 | 83 | 87 | 76 | 76.00 | 76 | 9.21 | 14.47 | 76 | 76.00 | 76 | 9.21 | 14.47 |
| | | | | 5 | 70 | 75 | 67 | 67.00 | 67 | 4.48 | 11.94 | 67 | 67.00 | 67 | 4.48 | 11.94 |
| 40 | 2 | 20 | 20 | 1 | – | – | 227 | 280.50 | 356 | – | – | 225 | 228.50 | 234 | – | – |
| | | | | 2 | 184 | 192 | 149 | 149.10 | 150 | 23.41 | 28.77 | 149 | 149.20 | 150 | 23.32 | 28.69 |
| | | | | 3 | 237 | 273 | 199 | 205.60 | 261 | 15.27 | 32.78 | 199 | 199.50 | 201 | 18.80 | 36.84 |
| | | | | 4 | 99 | 105 | 82 | 82.00 | 82 | 20.73 | 28.05 | 82 | 82.00 | 82 | 20.73 | 28.05 |
| | | | | 5 | 102 | 96 | 81 | 81.00 | 81 | 25.93 | 18.52 | 81 | 81.00 | 81 | 25.93 | 18.52 |
| 40 | 4 | 20 | 20 | 1 | 113 | 116 | 107 | 107.00 | 107 | 5.61 | 8.41 | 107 | 107.00 | 107 | 5.61 | 8.41 |
| | | | | 2 | 104 | 114 | 101 | 101.00 | 101 | 2.97 | 12.87 | 101 | 101.00 | 101 | 2.97 | 12.87 |
| | | | | 3 | 78 | 83 | 70 | 70.00 | 70 | 11.43 | 18.57 | 70 | 70.00 | 70 | 11.43 | 18.57 |
| | | | | 4 | 89 | 84 | 80 | 80.00 | 80 | 11.25 | 5.00 | 80 | 80.00 | 80 | 11.25 | 5.00 |
| | | | | 5 | – | 265 | 193 | 221.30 | 251 | – | 19.75 | 193 | 195.10 | 200 | – | 35.83 |
| | | | | | | | 103.70 | 108.20 | 116.40 | – | – | 103.60 | 103.97 | 104.75 | – | – |

Please cite this article in press as: Lalla-Ruiz, E., et al. The waterway ship scheduling problem. Transport. Res. Part D (2016), http://dx.doi.org/10.1016/j.trd.2016.09.013

**Table 8**

Comparison of $SA_{RG}$ and $SA_{STW}$ for the problem instances of 50 and 60 vessels. The benefits of using Simulated Annealing instead of algorithms based on queue rules (FCFS-G and STW-G) are shown.

| Instances | | | | | FCFS-G | STW-G | $SA_{RG}$ | | | | | $SA_{STW}$ | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\|V\|$ | $\|W\|$ | $\|V_1\|$ | $\|V_2\|$ | id | | | Min | Avg | Max | $Gap_{FCFS}$(%) | $Gap_{STW}$(%) | Min | Avg | Max | $Gap_{FCFS}$(%) | $Gap_{STW}$(%) |
| 50 | 2 | 25 | 25 | 1 | – | – | 172 | 197.40 | 236 | – | – | 172 | 173.80 | 176 | – | – |
| | | | | 2 | 155 | 150 | 108 | 108.20 | 109 | 43.25 | 38.63 | 108 | 108.50 | 109 | 42.86 | 38.25 |
| | | | | 3 | – | 342 | 242 | 244.80 | 247 | – | 39.71 | 241 | 243.00 | 248 | – | 40.74 |
| | | | | 4 | – | 464 | 324 | 365.20 | 481 | – | 27.05 | 325 | 326.90 | 330 | – | 41.94 |
| | | | | 5 | 112 | 122 | 100 | 100.00 | 100 | 12.00 | 22.00 | 100 | 100.00 | 100 | 12.00 | 22.00 |
| 50 | 4 | 25 | 25 | 1 | 116 | 115 | 100 | 100.00 | 100 | 16.00 | 15.00 | 100 | 100.00 | 100 | 16.00 | 15.00 |
| | | | | 2 | 96 | 85 | 82 | 82.00 | 82 | 17.07 | 3.66 | 82 | 82.00 | 82 | 17.07 | 3.66 |
| | | | | 3 | 119 | 128 | 107 | 107.00 | 107 | 11.21 | 19.63 | 107 | 107.00 | 107 | 11.21 | 19.63 |
| | | | | 4 | 92 | 93 | 82 | 82.00 | 82 | 12.20 | 13.41 | 82 | 82.00 | 82 | 12.20 | 13.41 |
| | | | | 5 | 87 | 128 | 78 | 78.00 | 78 | 11.54 | 64.10 | 78 | 78.00 | 78 | 11.54 | 64.10 |
| 60 | 2 | 30 | 30 | 1 | – | 305 | 239 | 267.10 | 312 | – | 14.19 | 237 | 239.20 | 241 | – | 27.51 |
| | | | | 2 | 252 | 318 | 199 | 205.00 | 243 | 22.93 | 55.12 | 198 | 200.30 | 204 | 25.81 | 58.76 |
| | | | | 3 | – | – | 520 | 529.60 | 591 | – | – | 443 | 445.80 | 447 | – | – |
| | | | | 4 | – | – | 326 | 348.50 | 374 | – | – | 290 | 290.80 | 291 | – | – |
| | | | | 5 | 341 | 392 | 266 | 337.00 | 393 | 1.19 | 16.32 | 262 | 268.80 | 272 | 26.86 | 45.83 |
| 60 | 4 | 30 | 30 | 1 | 93 | 120 | 75 | 75.00 | 75 | 24.00 | 60.00 | 75 | 75.00 | 75 | 24.00 | 60.00 |
| | | | | 2 | 139 | 148 | 115 | 115.30 | 117 | 20.56 | 28.36 | 115 | 115.70 | 117 | 20.14 | 27.92 |
| | | | | 3 | 95 | 96 | 83 | 83.00 | 83 | 14.46 | 15.66 | 83 | 83.00 | 83 | 14.46 | 15.66 |
| | | | | 4 | 201 | 261 | 187 | 188.10 | 189 | 6.86 | 38.76 | 188 | 188.10 | 190 | 6.86 | 38.76 |
| | | | | 5 | 125 | 125 | 106 | 106.00 | 106 | 17.92 | 17.92 | 106 | 106.00 | 106 | 17.92 | 17.92 |
| | | | | | | | 175.55 | 185.96 | 205.25 | – | – | 169.60 | 170.70 | 171.90 | – | – |

Please cite this article in press as: Lalla-Ruiz, E., et al. The waterway ship scheduling problem. Transport. Res. Part D (2016), http://dx.doi.org/10.1016/j.trd.2016.09.013

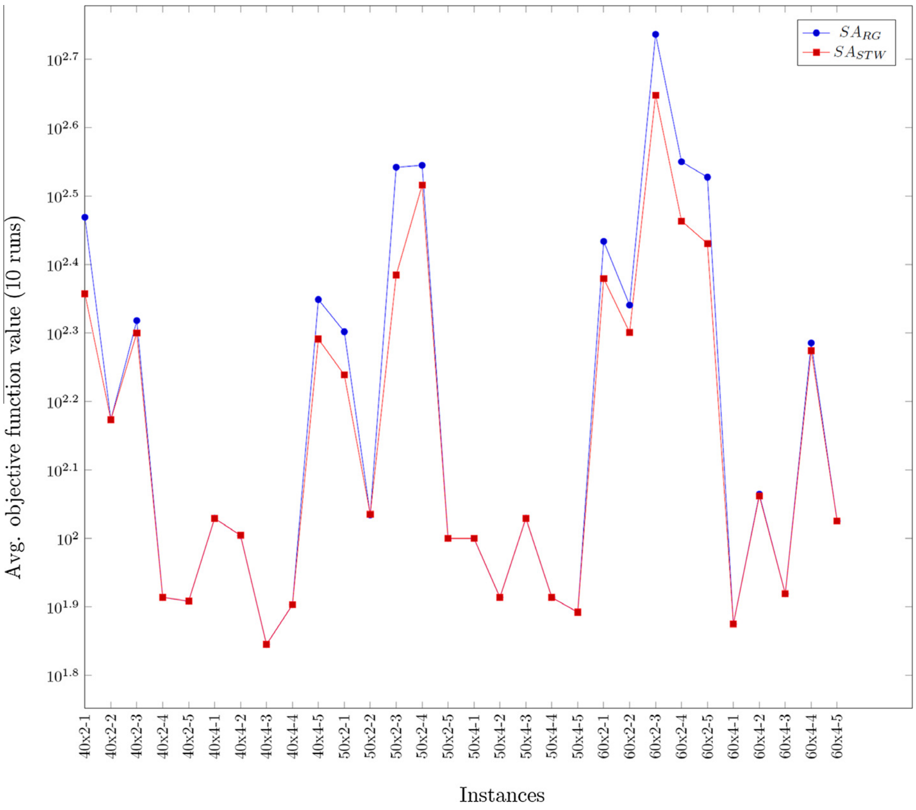

**Fig. 4.** Comparison between $SA_{RG}$ and $SA_{STW}$ in terms of average function value for 10 runs.

deployment. On the other hand, at a more strategic level, we seek to apply a respective tool to support decision makers to weight different options when discussing the provision of proper access to ports and terminals in case of capacity restricted transport corridors. One example in our mind refers to the case of the current discussion of the dredging of the Elbe river with its access to the port of Hamburg, Germany. Finally, from an algorithmic point of view, we will investigate the inclusion of different neighbourhood structures and their impact on the performance of the simulated annealing algorithm. This way we aim to provide, depending on the scenario, an intelligent way to select the most appropriate neighbourhood structure in an adaptive fashion.

## Acknowledgements

This work has been partially funded by the European Regional Development Fund, the Spanish Ministry of Economy and Competitiveness (project TIN2015-70226-R). Eduardo Lalla-Ruiz thanks the funding granted by the Canary Agency of Investigation, Innovation, and Information Society (ACIISI), 85% co-financed with the help of the European Social Fund. We thank the terminal operators of Waigaoqiao container terminal for the data provided.

## References

Bierwirth, C., Meisel, F., 2015. A follow-up survey of berth allocation and quay crane scheduling problems in container terminals. Eur. J. Oper. Res. 244 (3), 675–689.
Caldeirinha, V., Felício, J., 2014. The relationship between position-port, hard-port and soft-port characteristics and port performance: conceptual models. Marit. Policy Manage. 41 (6), 528–559.
Comtois, C., Dong, J., 2007. Port competition in the Yangtze river delta. Asia Pac. Viewpoint 48 (3), 299–311.
Cordeau, J.F., Laporte, G., Legato, P., Moccia, L., 2005. Models and tabu search heuristics for the berth-allocation problem. Transp. Sci. 39, 526–538.
Cordeau, J.-F., Laporte, G., Mercier, A., 2001. A unified tabu search heuristic for vehicle routing problems with time windows. J. Oper. Res. Soc. 52 (8), 928–936.
Dai, M.D.M., Schonfeld, P., 1998. Metamodels for estimating waterway delays through series of queues. Transp. Res. Part B: Methodol. 32 (1), 1–19.
De Vriend, H.J., Wang, Z.B., Ysebaert, T., Herman, P., Ding, P., 2011. Eco-morphological problems in the Yangtze Estuary and the Western Scheldt. Wetlands 31 (6), 1033–1042.
Deng, X., Li, Y., Zhao, Y., 2011. Overview of research on traffic capacity of harbor channel. Port Waterway Eng. 3, 003.
Douma, A., Schuur, P., Jagerman, R., 2011. Degrees of terminal cooperativeness and the efficiency of the barge handling process. Expert Syst. Appl. 38 (4), 3580–3589.

Please cite this article in press as: Lalla-Ruiz, E., et al. The waterway ship scheduling problem. Transport. Res. Part D (2016), http://dx.doi.org/10.1016/j.trd.2016.09.013

Dowsland, K., Soubeiga, E., Burke, E., 2007. A simulated annealing based hyperheuristic for determining shipper sizes for storage and transportation. Eur. J. Oper. Res. 179 (3), 759–774.

Du, Y., Chen, Q., Lam, J., Xu, Y., Cao, J., 2015. Modeling the impacts of tides and the virtual arrival policy in berth allocation. Transp. Sci.

Du, Y., Chen, Q., Quan, X., Long, L., Fung, R., 2011. Berth allocation considering fuel consumption and vessel emissions. Transp. Res. Part E: Logist. Transp. Rev. 47 (6), 1021–1037.

Fagerholt, K., Laporte, G., Norstad, I., 2010. Reducing fuel emissions by optimizing speed on shipping routes. J. Oper. Res. Soc. 61 (3), 523–529.

Golden, B., Raghavan, S., Wasil, E. (Eds.), 2008. The Vehicle Routing Problem: Latest Advances and New Challenges. Operations Research/Computer Science Interfaces, vol. 43. Springer, New York.

Günther, E., Lübbecke, M.E., Möhring, R.H., 2010. Ship traffic optimization for the Kiel canal. In: Seventh Triennial Symposium on Transportation Analysis (TRISTAN 2010).

Günther, E., Lübbecke, M.E., Möhring, R.H., 2011. Challenges in scheduling when planning the ship traffic on the Kiel canal. In: 10th Workshop on Models and Algorithms for Planning and Scheduling Problems (MAPSP 2011).

Hartl, R.F., Hasle, G., Janssens, G.K., 2006. Special issue on rich vehicle routing problems. CEJOR 14 (2), 103–104.

Kirkpatrick, S., Gelatt Jr., C.D., Vecchi, M.P., 1983. Optimization by simulated annealing. Science 220 (4598), 671–680.

Kontovas, C., Psaraftis, H., 2011. Reduction of emissions along the maritime intermodal container chain: operational models and policies. Marit. Policy Manage. 38 (4), 451–469.

Kosmas, O.T., Vlachos, D.S., 2012. Simulated annealing for optimal ship routing. Comput. Oper. Res. 39 (3), 576–581.

Lalla-Ruiz, E., Voß, S., 2016. Popmusic as a matheuristic for the berth allocation problem. Ann. Math. Artif. Intell. 76 (1–2), 173–189.

Lenstra, J., Rinnooy Kan, A., 1981. Complexity of vehicle routing and scheduling problems. Networks 11 (2), 221–227.

Liang, C., Huang, Y., Yang, Y., 2009. A quay crane dynamic scheduling problem by hybrid evolutionary algorithm for berth allocation planning. Comput. Ind. Eng. 56 (3), 1021–1028.

Liu, J., Han, X., Yi, X., 2008. Capacity analysis of restricted channels based on the queuing theory. Navig. China 3, 014.

Lorenzoni, L., Ahonen, H., de Alvarenga, A., 2006. A multi-mode resource-constrained scheduling problem in the context of port operations. Comput. Ind. Eng. 50 (1), 55–65.

Lowe, D., 2005. Inland waterway, short-sea, and coastal shipping. In: Lowe, D. (Ed.), Intermodal Freight Transport. Butterworth-Heinemann, Oxford, pp. 92–109.

Moon, D., Woo, J., 2014. The impact of port operations on efficient ship operation from both economic and environmental perspectives. Marit. Policy Manage. 41 (5), 444–461.

Ning, S., Song, X., Guo, Z., Li, J., Lu, C., 2008. Study on unidirectional waterway transit capacity with simulation. J. Waterway Harbor 3, 002.

Notteboom, T., 2006. The time factor in liner shipping services. Marit. Econ. Logist. 8 (1), 19–39.

Notteboom, T., 2007. Container river services and gateway ports: similarities between the Yangtze river and the Rhine river. Asia Pac. Viewpoint 48 (3), 330–343.

Notteboom, T., 2008. The Relationship Between Seaports and the Inter-modal Hinterland in Light of Global Supply Chains. Discussion Paper 2008-10. OECD/ITF.

Smith, L.D., Nauss, R.M., Campbell, J.F., Sweeney, D.C., 2009. Triangulation of modeling methodologies for strategic decisions in an inland waterway transportation system. In: 42nd Hawaii International Conference on System Sciences. IEEE, pp. 1–10.

Smith, L.D., Nauss, R.M., Mattfeld, D.C., Li, J., Ehmke, J.F., Reindl, M., 2011. Scheduling operations at system choke points with sequence-dependent delays and processing times. Transp. Res. Part E: Logist. Transp. Rev. 47 (5), 669–680.

Solomon, M., 1987. Algorithms for the vehicle routing and scheduling problems with time window constraints. Oper. Res. 35 (2), 254–265.

Song, S., 2014. Ship emissions inventory, social cost and eco-efficiency in Shanghai Yangshan port. Atmos. Environ. 82, 288–297.

Taylor, G.D., Whyte, T.C., DePuy, G.W., Drosos, D.J., 2005. A simulation-based software system for barge dispatching and boat assignment in inland waterways. Simul. Model. Pract. Theory 13 (7), 550–565.

Ulusçu, Ö.S., Özbaş, B., Altıok, T., Or, İ., Yılmaz, T., 2009. Transit vessel scheduling in the strait of Istanbul. J. Navig. 62 (1), 59–77.

UNCTAD, 2014. Review of Maritime Transport. Technical Report. United Nations Conference on Trade and Development (UNCTAD) – Secretariat, 2014. <http://unctad.org/en/PublicationsLibrary/rmt2014_en.pdf>.

United Nations Economic and Social Commision for Asia and the Pacific (UNESCAP), 2004. Transport Division (TD). Manual on Modernization of Inland Water Transport for Integration Within a Multimodal Transport System. United Nations.

Verstichel, J., De Causmaecker, P., Spieksma, F.C.R., Vanden Berghe, G., 2014. Exact and heuristic methods for placing ships in locks. Eur. J. Oper. Res. 235, 387–398.

Verstichel, J., De Causmaecker, P., Spieksma, F., Berghe, G.V., 2011. The Generalized Lock Scheduling Problem: An Exact Approach. Technical Report. KAHO Sint-Lieven.

Voß, S., 2001. Meta-heuristics: the state of the art. In: Local Search for Planning and Scheduling. Springer, pp. 1–23.

Yang, G., 1995. Transformation of multidepot multisalesmen problem to the standard travelling salesman problem. Eur. J. Oper. Res. 81, 557–560.

Yang, J., Gao, Q., Chen, T., 2008. Interactive relationship between container transport and regional economic development: a perspective of port clusters in the Yangtze river delta. Port Waterway Eng. 11, 029.

Yang, Z., Shi, H., Chen, K., Bao, H., 2014. Optimization of container liner network on the Yangtze river. Marit. Policy Manage. 41 (1), 79–96.

Yap, W.Y., Lam, J.S.L., 2013. 80 million-twenty-foot-equivalent-unit container port? Sustainability issues in port and coastal development. Ocean Coast. Manage. 71, 13–25.

Zhou, J., Hu, Y., 2004. Solutions to selection of anchorage in Ningbo port based on AHP. J. Zhejiang Ocean Univ. 4, 008.