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A simulation-based approach for assessing seaside infrastructure improvement measures for large marine crude oil terminals

Abstract

We develop detailed simulation models for examining how various seaside infrastructure improvement measures of a marine crude oil terminal can increase its maximum oil throughput, reduce tanker delays, and minimize the total system cost over a certain planning horizon. The models account for special navigation constraints for oil tankers, realistic tidal constraints, and practical priority rules for different tanker types at the Rizhao Shihua Oil Terminal in China. Results show that the most cost-effective measure is adding a buffer to increase the one-way channel's tanker-handling capacity. This novel, low-cost measure thus holds much promise for real-world implementation.

Keywords: crude oil terminals; port operations; simulation; one-way channel; buffer area

1 Introduction

Due to the low cost of maritime transport, it has long been the predominant means for international crude oil shipping. In 2015, 61% of the global crude oil and petroleum products were transported by marine vessels (TBP, 2017). For China, the world's largest crude oil importer, 89% of its imports were carried by oil tankers in 2018 (SSE, 2019), totaling 461.9 million tons and a value of 239.2 billion USD (Export.gov, 2019; Workman, 2019). The rapid growth of China's crude oil import (see Figure 1) is expected to continue due to its economic boom. As a result, the maritime oil transportation would keep going up as well.

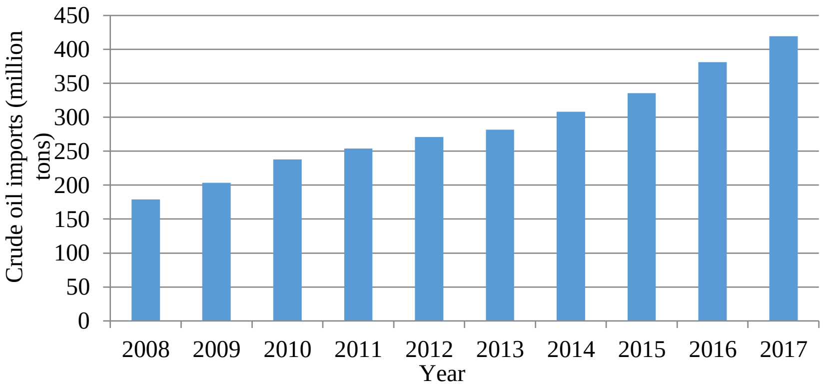

Figure 1. Crude oil imports in China from 2008 to 2017 (data extracted from NBS, 2008-2017)

The ever-growing demand has imposed great challenge on the existing marine oil terminals in China. Although 21 very-large-crude-carrier (VLCC) berths have been built along Chinese coastline (Sohu, 2019), many tankers still experienced severe congestion and delays at Chinese oil terminals (S&P Global Platts, 2019). For example, in May 2016 the average port delay of oil tankers at Qingdao Port hit a record high of 20-30 days (Wang, 2018). Significant delays entail great costs. For a VLCC, each day's delay may incur a tanker rent of 28,000 USD (Frontline Ltd., 2019) and an oil holding cost of approximately 30,000 USD[1], totaling 58,000 USD/day. Even greater costs were often incurred due to the rollercoaster ride of oil prices over past decades (Raval and Winter, 2018).

Due to the ever-growing tanker demand and the enormous costs associated with port delays, existing oil terminal infrastructures often need improvements and expansions. On the other hand, excess construction as a consequence of myopic planning is also undesirable. This is especially true given the highly volatile international crude oil market (Raval and Winter, 2018). Hence, a realistic and accurate model of tanker queues is needed for estimating a real-world terminal's oil throughput and expected tanker delays, and for assessing and comparing various terminal infrastructure improvement measures.

[1] An oil price of 60 USD/barrel and an annual interest rate of 8% are assumed.

It should be able to account for the complexities arising in oil terminal operations, including: i) the stochastic tanker demand over a long planning horizon, with various tanker types, oil loads, and drafts; ii) dynamic climate and hydrological (e.g. tidal) conditions; iii) the tanker navigation process through a complex terminal layout; and iv) special navigation rules for ensuring the safety in transporting hazardous goods (crude oil herein).

Previous studies often model vessel and port operations analytically. These include economics models on higher-level planning that involve port competition (Wan et al., 2016; Wang and Zhang, 2018), and optimization models on, e.g., container shipping liner planning and operations (Brouer et al., 2014; Wang et al., 2014; Song et al., 2015; Zhen et al., 2019). These analytical studies examined larger-scope maritime systems beyond the terminal level, and unveiled useful insights into policy, planning, and management decisions for those systems. However, vessels' port operations examined in these studies are often simpler than what actually occur in crude oil terminals. Thus, their models cannot be directly applied to solve the research question of interest here. The same is true for the analytical methods developed for solving the so-called "berth allocation problems (BAP)" (Imai et al, 2001; Bierwirth and Meisel, 2010, 2015; Zhen et al., 2011; Carteni and de Luca, 2012; Zhen and Chang, 2012; Wang et al., 2013; Cantarella et al., 2015; Iris et al., 2017; Xiang et al., 2017; Wang et al., 2018). These BAP studies aim to optimize the temporal allocation of berths to the vessels at the operational level, while our research question concerns the strategic planning of port infrastructure over a long planning horizon. The latter requires to examine the expected performance metrics of the port queueing system considering stochastic and time-varying vessel arrivals. There also exist a few studies that solved stochastic vessel queues analytically (e.g. Altiok, 2000; Jagerman and Altiok, 2003; Saeed and Larsen, 2016). However, those analytical methods were developed for special or simple cases of vessel queues. Complicated queueing systems like large crude oil terminals are usually analytically intractable.

On the other hand, simulation techniques have been commonly used for modeling complex and realistic queues that do not have an analytical solution (e.g. Paolucci et al., 2002; Shabayek and Yeung, 2002; Cortés et al., 2007; Gu et al., 2011; Almaz and Altiok, 2012; Cimpeanu et al., 2015; 2017). These simulation models derived general system performance metrics such as cargo throughputs, vessel delays, berth utilization, etc., for various types of ports and waterways. Simulation models were also used to assess the effects of certain infrastructure improvement measures, e.g., adding berths (Kozan, 1994; Alattar et al., 2006), dredging the channel or port basin (Cortés et al., 2007; Quy et al., 2008; Almaz and Altiok, 2012; Tang et al., 2014a), upgrading the unloading facilities (Feng et al., 2015), and novel strategies such as using a buffer to accommodate two-way vessel traffic in a one-way channel (Song et al., 2012; Tang et al., 2014b; Tang and Qi, 2018).

In light of the above, we develop new simulation models for emulating the tanker operations at large-scale crude oil terminals. Compared to the existing simulation studies on port operations, our work has the following novelties:

i) Our models account for the special navigation rules that are enacted for a single one-way channel serving inbound and outbound tankers alternately. A crude oil terminal often has only a single one-way channel due to its cost advantage (Koele and Don, 1971; Wu, 2012; Jeong, 2016). To avoid conflicts between oil tankers, the port management agency often stipulates empirical priority rules for multiple tankers calling for the use of channel simultaneously. Additional rules are also enacted to ensure safe tanker navigation since crude oil is a hazardous good. These include the daytime constraint for tanker navigation and the minimum tanker spacing constraint in the channel. To our best knowledge, we are the first to model those navigation rules that are specially designed for crude oil terminals. Many previous studies have assumed a two-way channel or two one-way channels, one for the inbound traffic and the other for the outbound (e.g., Quy et al., 2008). Only a handful of works have examined a single one-way channel for serving bi-directional traffic (e.g. Tang et al., 2014a; Tang and Qi, 2018). However, only simple, First-Come-First-Served (FCFS) navigation rules were assumed in the above-cited papers.

ii) Our work faithfully simulated the real, day-to-day dynamic tidal cycles (Quy et al., 2008). Previous studies either ignored the impacts of tidal levels on vessel navigation (Shabayek and Yeung, 2002; Huang et al., 2013; Xiao et al., 2013), or simply assumed fixed tidal time windows for vessel navigation (e.g., Cimpeanu et al., 2015). We show in this paper why the accurate modeling of tidal cycles is necessary for simulating crude oil terminal operations, and how unexpected errors may occur if simplified modeling methods like those employed in the literature were used instead.

iii) Our simulation models are employed to examine a number of port infrastructure improvement measures, including berth adding, channel dredging (both in depth and in width), buffer deployment, and their combinations. This enables an extensive comparison between the performance and costs of those measures. Such a comparison was also absent in the literature, since most works have focused on only one type of infrastructure improvement (Alattar et al., 2006; Almaz and Altiok, 2012; Saeed and Larsen, 2016; Ahadi et al., 2018; Tang and Qi, 2018). Built upon the simulation results, we further examine the optimal scheduling of multiple, mixed-type improvement activities over a long planning horizon. To our best knowledge, this has also been overlooked in the literature.

Our models only simulate the seaside operations of the terminal, as illustrated in Figure 2. This part of terminal operations can be divided into two subsystems: i) a navigation subsystem that contains tanker anchorages and a one-way channel (termed the "main channel") connecting to the dockyard; and ii) a dockyard that contains dwelling berths and a turning basin where tankers make turning maneuvers before entering berths and after exiting berths. We do not model the upstream oil delivery (i.e., tankers' transportation from the origin ports to the destinations) and the downstream oil distribution (involving tank farms, inland transportation via pipelines, roads and waterways, and refineries), since they are not part of the seaside terminal operations.[2] The simulation is used to explore the effects of four seaside infrastructure improvement measures, namely, adding berths, expanding the channel to a two-way one, deepening the channel to eliminate the tankers' dependency on high tides, and adding a buffer area. Specifically, we examine the annual crude oil throughput for each of the above improvement measures, and their resulting average tanker delays under given demands. We further analyze the total discounted system cost over a 10-year planning horizon to identify the optimal schedule of infrastructure improvement activities.

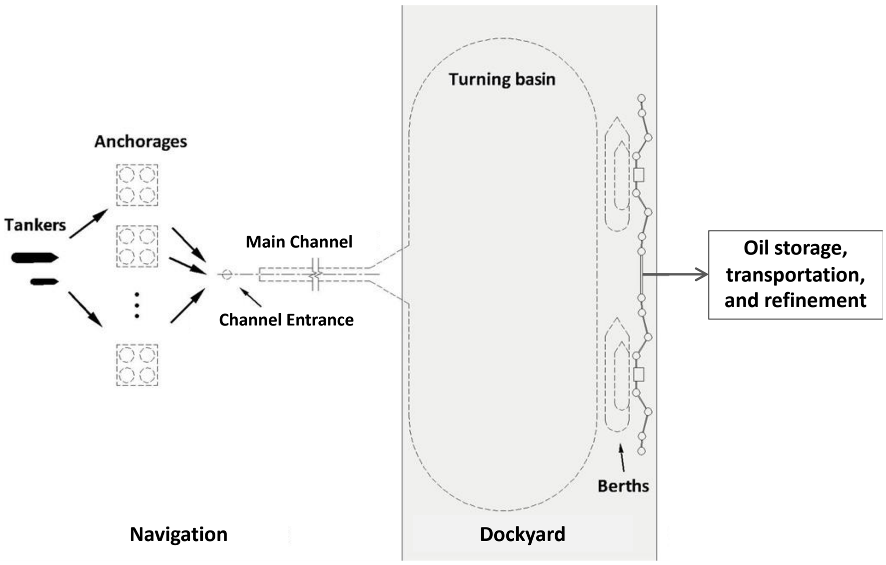

Figure 2. Components of a crude oil terminal (the seaside)

[2] The downstream oil distribution system may become bottlenecks for the crude oil unloading operations at oil terminals. This effect can be accounted for by simply adding an on/off server calibrated to the historical data, given that the data are available. For the case examined in this paper, the downstream oil distribution system was seldom an active bottleneck according to the port management agency.

The simulation models are developed using the layout and data of the Rizhao Shihua Oil Terminal (RSOT), located in the Lanshan District of Rizhao Port, Shandong, China; see Figure 3. Consisting of three 300,000 DWT (deadweight tonnage) berths, the RSOT is ranked the third-largest in China in terms of annual oil import. Despite the high handling capacity, tankers visiting the RSOT still experienced significant delays. For example, in 2018 some tankers had to queue up for over 4 days before they were allowed to approach the berths (RSOT, 2018). On the other hand, the RSOT also competes for tankers against neighboring crude oil terminals including the Qingdao Port, the Dalian Port, and the Tianjin Port; see again Figure 3. The competition would be intensified as the crude oil supply fluctuates. Hence, the RSOT desires simple and reliable estimates of its long-term oil throughput, tanker delays, and overall costs. These estimates will help the port management agency make decisions regarding seaside infrastructure improvements in the next decade.

The rest of the paper is organized as follows. Section 2 describes the tankers' operation processes. Section 3 defines the four types of infrastructure improvement measures. Section 4 presents the simulation model development, and the results on the annual crude oil throughput and average tanker delays. Section 5 explores the optimal infrastructure improvement schedule over the next 10 years. Section 6 summarizes the findings and discusses opportunities for future research.

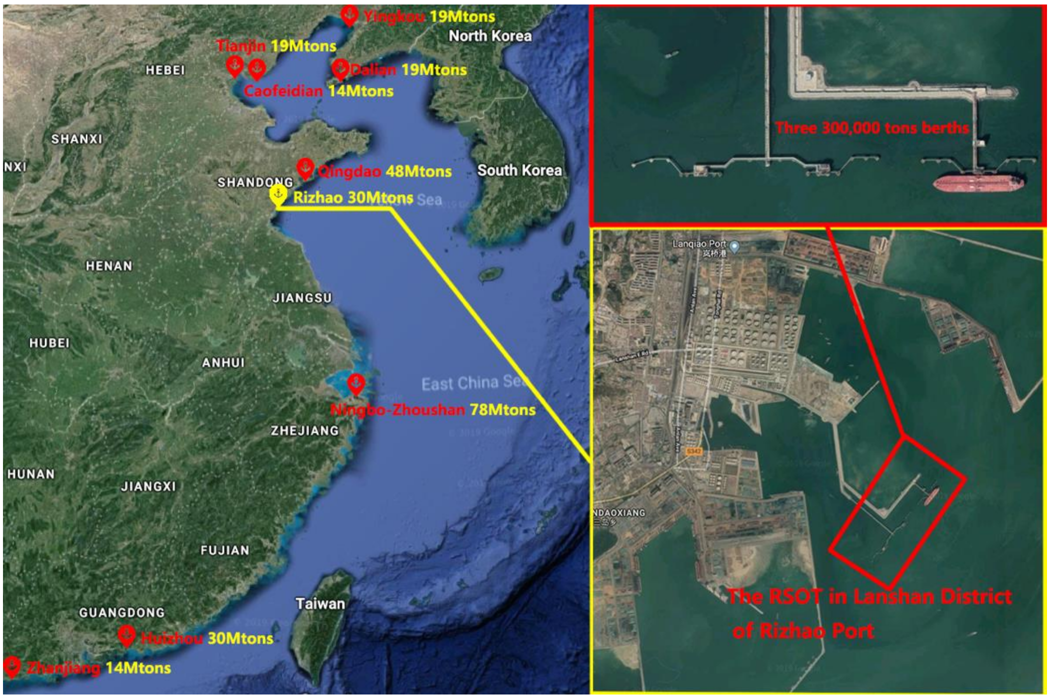

Figure 3. Geographic locations of RSOT and neighboring crude oil terminals

2 Tankers' operation processes at the RSOT

The types of oil tankers and their operating parameter values (including the actual oil loadings, unloading times, drafts, and arrival process) are presented in section 2.1. The layout of the port is described in section 2.2. A tanker's service process at the port is defined in section 2.3. The conditions that regulate tankers' inbound and outbound navigation are explained in section 2.4.

2.1 Tanker characteristics

2.1.1 Tanker types

Data collected by the RSOT showed that three types of oil tankers, namely the VLCCs, the Aframaxes and the Suezmaxes, have visited the RSOT from 2010-2014 (Jin, 2017). Their shares and tonnages are given in Table 1.

Due to the large sizes and drafts of VLCCs, they have to use a different anchorage area located farther from the shoreline, and their navigation in and out of the port follows a different set of rules from the Aframax and Suezmax tankers. For example, laden VLCCs may have to take the high tide when navigating through the main channel due to their deep drafts, while Aframaxes and Suezmaxes can freely enter the channel at any tidal level even if they are fully loaded. On the other hand, Aframaxes and Suezmaxes are similar in that they use the same anchorage area and follow the same navigation rules. Moreover, Suezmaxes have a very small share at the RSOT. Hence, in the interest of brevity, we assume that there are only two tanker types, 100,000 DWT and 300,000 DWT, and that the former has a share of 10.8% (combining the shares of Aframaxes and Suezmaxes). Note that the shares of different tanker types are by-and-large invariant in the past decades for both the RSOT and the global market (Li, 2014). Hence, we assume that these shares stay constant when modeling the port operations for future years.

Table 1. Types of oil tankers visiting the RSOT

Tanker type	**Tonnage (DWT)**	**Proportion**
VLCC	250,000-300,000	89.2%
Aframax	80,000-100,000	9.2%
Suezmax	150,000-180,000	1.6%

2.1.2 Arrival process

A tanker's arrival time is defined as the time when it enters an anchorage area. Both anchorage areas are assumed to have infinite capacity, and thus no tanker will queue up at the entrance of an anchorage.[3] Due to the lack of available data, we assume that the tankers' inter-arrival times (regardless of their type) follow an Erlang-2 distribution. That type of distribution was shown to fit the real tanker arrival data in a neighboring crude oil terminal (Feng et al., 2015). The mean inter-arrival time is set to the inverse of the number of tankers served in a year.

2.1.3 Actual oil loadings, drafts, and unloading times

Since the RSOT does not provide the detailed tanker loading data, we assume that the tanker loadings for 100,000 DWT tankers and 300,000 DWT tankers are random variables whose distributions are given as follows. For 100,000 DWT tankers, we fit a transformed beta distribution to the tanker loading data at a neighboring 100,000 DWT berth during 2009-2012 (Zhang et al., 2013). The distribution is denoted by $4.39 \times 10^4 + 6.02 \times 10^4 \times BETA(0.979, 0.427)$, where $BETA(0.979, 0.427)$ denotes a standard beta-distributed random variable with shape parameters 0.979 and 0.427[4]. We further assume that the oil loadings of the 300,000 DWT tankers follow another transformed beta distribution of the same shape, which is denoted by $9.73 \times 10^4 + 13.25 \times 10^4 \times BETA(0.979, 0.427)$. The location and scale parameters of the distribution, i.e. 9.73×10^4 and 13.25×10^4, are selected so that the average loading per tanker and the fraction of tankers carrying half-load or less match the rough estimates provided by the RSOT (RSOT, 2018).

A 300,000 DWT tanker's draft is calculated from its loading via the following empirical formula, which is regressed from the draft data of 27 VLCCs visiting the RSOT in 2009-2012 (Zhang et al., 2013). The R^2 of the regression is 0.962.

$$d = \frac{w}{27800} + 10 \quad (1)$$

where d and w denote the draft (in meters) and the loading (in tons) of a 300,000 DWT tanker, respectively. Draft data of 100,000 DWT tankers are not needed since even a fully-loaded 100,000 DWT tanker can pass the channel at any tidal level.

[3] Under the rare cases where an anchorage is full and some tankers have to wait outside, those tankers can still be considered as part of the queue in the anchorage since they can enter the anchorage immediately should a vacant space become available. Hence, this assumption will not affect our simulation results.

[4] This distribution attains the best goodness of fit among a number of candidates, with a p-value of over 0.15 in the Kolmogorov-Smirnov test.

A tanker's unloading time at the berth equals its oil loading divided by the unloading rate. Different unloading facilities are used at the RSOT for 100,000 DWT and 300,000 DWT tankers, with unloading rates of 5000 tons/hour and 8000 tons/hour, respectively. We assume that all the tankers visiting the RSOT will empty their load at the port.

Note here that we ignore the detailed size of each tanker, since a VLCC's draft depends mainly on its loading.[5]

2.2 Layout of the oil terminal

As illustrated by Figure 4, the 100,000 DWT Anchorage and the 300,000 DWT Anchorage are located 8.5 km and 23.6 km from the channel entrance, respectively. The one-way main channel connecting to the dockyard is 27.8 km long. Three berths and a turning basin are located in the dockyard. The turning basin can serve only one tanker at a time.

2.3 Tankers' service process

A tanker's inbound process consists of the following steps:

Step 1. Arriving to the corresponding anchorage area.

Step 2. Departing the anchorage for the channel entrance when all the conditions (e.g. channel availability, tidal level) are satisfied. The tanker cruises at 16 km/hour regardless of its type.

Step 3. Traveling through the main channel to the dockyard. For safety reasons, this is done with the help of tugboats. According to the RSOT, a tanker takes 2 hours to travel through the channel, regardless of its type.

Step 4. Entering a berth. After the tanker enters the dockyard, the tugboats will push its head to turn around in the turning basin. This maneuver takes 1 hour and 1.5 hours for 100,000 DWT and 300,000 DWT tankers, respectively. The tanker will then enter one of the three berths in the dockyard, which should have been reserved before it departs the anchorage.

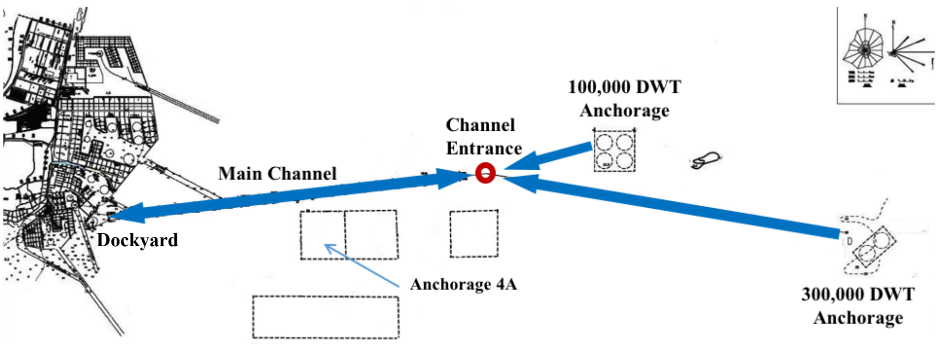

Figure 4. Layout of the RSOT

A reverse process is performed when the tanker completes unloading of the oil and exits the berth. This includes a reverse turning maneuver in the turning basin, traveling through the channel outbound, and departing the port. The tanker will not enter the anchorage again before its departure.

The detailed inbound, dwelling, and outbound processes of a tanker are illustrated in Figure 5.

[5] We have also conducted simulation tests where each tanker's draft is assumed to follow a uniform distribution that ranges from 90% to 110% of the result of equation (1). Results show that the errors seldom exceed 2%. This indicates that the effect of ship size on the draft is negligible.

2.4 Navigation rules and conditions

Section 2.4.1 summarizes the safety rules for oil tanker navigation and operations. Section 2.4.2 describes the tidal constraints for 300,000 DWT inbound tankers. Section 2.4.3 presents the priority rules set by the RSOT.

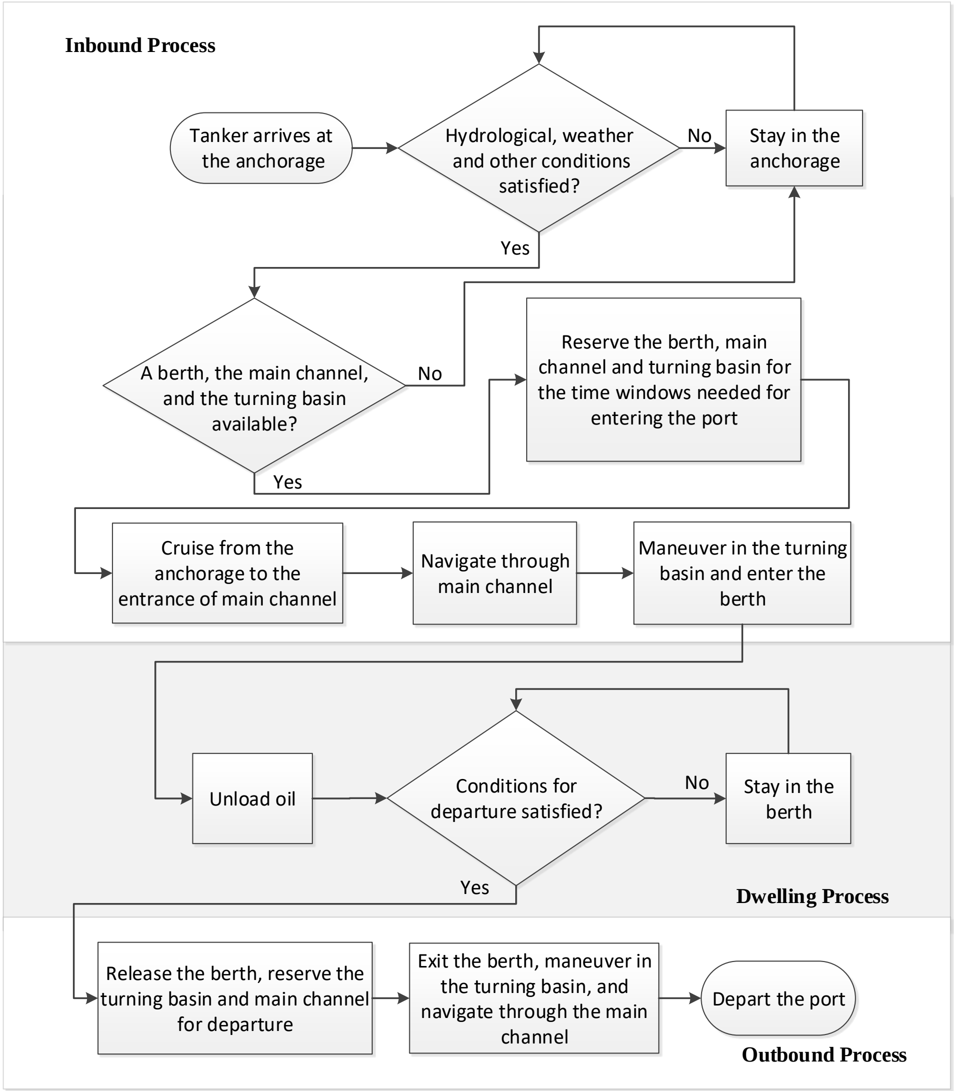

Figure 5. Flow chart for a tanker's service process

2.4.1 Safe navigation and operating rules

For an inbound tanker, the following conditions (a-e) must be satisfied before it is allowed to depart the anchorage for the dockyard.

(a) Once a tanker departs the anchorage, it must travel all the way to the berth without any stop.

(b) No extreme weather is present. Three types of extreme weather conditions are considered: strong wind, fog, and high wave. They are assumed to occur on any specific day at fixed probabilities denoted by p_{sw}, p_f, and p_{hw}, respectively. According to the historical weather data of the RSOT during the past 16 years, we specify that $p_{sw} = \frac{14}{365}$, $p_f = \frac{11}{365}$, and $p_{hw} = \frac{3}{365}$.

(c) The tanker's navigation in the main channel and its maneuver in the turning basin must be performed during the daytime. The daytime is specified to be 6am to 6pm according to the port agency.

(d) When the tanker departs the anchorage, at least one berth must be available and not reserved by any other tankers. For the safety reason, a berth that is currently occupied by a tanker cannot be reserved for a future time.

(e) The main channel and the turning basin are available for the time windows used by the present inbound tanker, but they do not have to be available at present. An inbound tanker and an outbound one cannot be both present in the main channel. Two inbound tankers must maintain a minimum headway of 2 hours in the channel, which also effectively prohibits two inbound tankers from appearing simultaneously in the channel.

Conditions (c-e) are special requirements for ensuring the safe navigation of crude oil tankers.

When dwelling in a berth, the tanker will unload oil continuously day and night. The unloading operation only halts during strong wind and high wave days.

An outbound tanker can depart the berth if the above conditions (b), (c), and the following condition (f) are all satisfied.

(f) The turning basin and the main channel are available for the time windows used by the outbound tanker. Two outbound tankers can navigate through the channel at the same time, if a minimum headway of 1.5 hours is maintained.

2.4.2 Tidal constraints

Tidal constraints only apply to 300,000 DWT inbound tankers, since laden 100,000 DWT tankers and empty 300,000 DWT tankers can pass the channel even at the lowest tide. Specifically, the RSOT stipulates that a laden 300,000 DWT tanker can navigate through the main channel only when the water depth is greater than a threshold, βd, where d is the tanker's draft calculated by equation (1), and β is a safety coefficient that equals 1.15. Although the above rule overlooks various factors (e.g. the tanker's squat, rolling, pitching, and sagging) that affect a tanker's Under Keel Clearance, it is simple and conservative.

The RSOT has a semi-diurnal tide with a period of approximately 12.4 hours. The highest and lowest tidal levels of a period vary roughly in a cyclic pattern, and each cycle is approximately 15 days long (containing 29 semi-diurnal periods; see an illustration in Figure 6. We then formulate the tidal constraints for a laden 300,000 DWT tanker as follows:

$$h(TNOW + t_3) \geq \beta d \tag{2}$$

$$h(TNOW + t_3 + t_c) \geq \beta d \tag{3}$$

$$\begin{cases} \dot{h}(TNOW + t_3) \geq 0 \text{ and } \dot{h}(TNOW + t_3 + t_c) \geq 0, & \text{or} \\ \dot{h}(TNOW + t_3) \leq 0 \text{ and } \dot{h}(TNOW + t_3 + t_c) \leq 0, & \text{or} \\ \dot{h}(TNOW + t_3) > 0 \text{ and } \dot{h}(TNOW + t_3 + t_c) < 0, & \text{or} \\ \dot{h}(TNOW + t_3) < 0 \text{ and } \dot{h}(TNOW + t_3 + t_c) > 0 \text{ and } h_{lowest} \geq \beta d \end{cases} \tag{4}$$

where $h(\cdot)$ indicates the channel's water depth as a function of time, and $\dot{h}(\cdot)$ its first order derivative; $TNOW$ denotes the present time; t_3 the navigation time from the anchorage to the channel entrance; t_c the travel time through the main channel; and h_{lowest} the minimal water depth in the present tidal period. Inequalities (2) and (3) specify that the water depth should be no less than βd when the tanker enters and leaves the main channel, respectively. Constraint (4) further ensures that the water depth is always no less than βd when the tanker is traveling in the channel. Specifically, the first line of (4) represents the case of a rising tide (flood) when the tanker is in the channel; the second line represents the case of a falling tide (ebb); the third line represents the case where a high tide is contained in the tanker's navigation duration; and the last line represents the case where a low tide is contained in that duration.

For simplicity, we assume $h(\cdot)$ is periodic for 15-day cycles. This function is obtained by averaging the water depth data at the RSOT in year 2015, extracted from a software named "Chinatide" (Li and Zheng, 2007). The $\dot{h}(\cdot)$ in (4) is approximated by taking the first order differences of $h(\cdot)$ for a sufficiently small interval (e.g. 10 minutes).

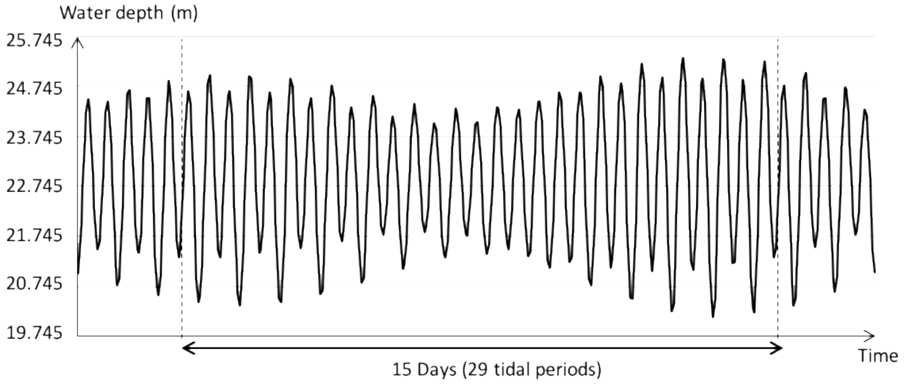

Figure 6. The water depth curve at the RSOT

We note that the semidiurnal tides were often simplified as two fixed tidal periods per day in previous studies on port operations (e.g., Tang et al., 2014; Cimpeanu et al., 2015, 2017). However, the simplification is a coarse approximation of the real case, in which there are 29 periods per 15 days, and the periods are postponed by 48 minutes each day. This approximation can potentially create sizeable errors for modeling crude oil terminal operations, since tanker navigations must be performed during daytime. For illustration, Figure 7 shows the navigation time windows satisfying both high tide and daytime constraints as orange bars. Note that these time windows vary across days, and that they are largely different from the case with two fixed tidal periods per day. Furthermore, each VLCC in our simulation has a different required water depth level due to the random oil loading (see section 2.1.3) and this adds to the complexity of the issue. We will see in section 4.4 that our method (henceforth termed the "realistic tidal cycle model", or the realistic model) can generate significantly more accurate results than the simplified models used in the literature under certain conditions.

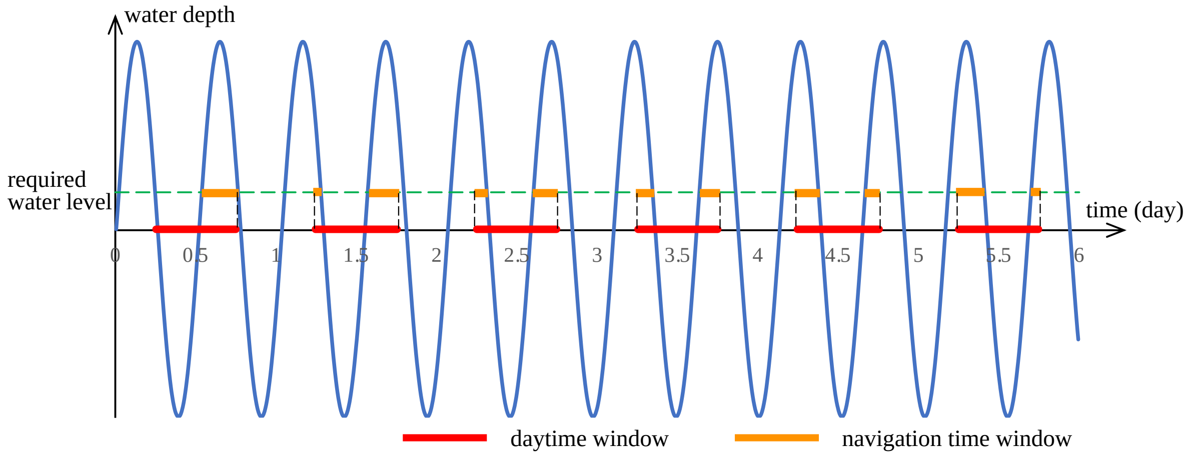

Figure 7. The navigation time windows satisfying both high tide and daytime constraints (for the brevity and clarity of illustration, all the tidal cycles are assumed to be identical)

2.4.3 Priority rules

The simulation employs the priority rules stipulated by the RSOT to govern how various types of tankers are served in turn. They are explained as follows:

(g) When two or more tankers of the same type and direction (inbound or outbound) satisfy the navigation conditions at the same time, they will be served in a FCFS order; i.e., the first one that arrives to the anchorage (for inbound tankers) or finishes unloading (for outbound tankers) will be allowed to proceed first.

(h) When two or more tankers of different types or directions are ready at the same time, they will be processed in the following order: 300,000 DWT inbound tankers are served first, followed by 100,000 DWT inbound tankers, 300,000 DWT outbound tankers, and 100,000 DWT outbound tankers in turn. This order is set to prioritize large tankers over smaller ones, and inbound tankers over outbound ones, since large and inbound tankers have higher holding costs.

(i) Suppose a 300,000 DWT tanker and a 100,000 DWT tanker are both awaiting in their anchorages and they satisfy the following conditions: i) all the navigation conditions are satisfied for the 100,000 DWT; ii) only the tidal constraints are not satisfied for the 300,000 DWT, but they will be satisfied in a few hours; and iii) allowing the 100,000 DWT tanker to enter first will delay the entry of the 300,000 DWT tanker. Then the 100,000 DWT tanker will be held to let the 300,000 DWT tanker enter first when the tidal constraints become satisfied.

(j) To prevent extremely long delays for 100,000 DWT tankers, a 100,000 DWT tanker will be prioritized if its wait time in the anchorage exceeds 100 hours. This rule overrides rules (g-i).

3 Measures of improvement

Three bottlenecks may occur in this port: the berths, the main channel, and the turning basin. The tanker-handling capacity at the first two bottlenecks can be increased by the following seaside infrastructure improvement measures:

i) Add more berths to the dockyard.

ii) Expand the channel to accommodate two-way tanker traffic simultaneously. This requires that the current channel width, 390m, is expanded to 560m.

iii) Dredge the channel so that a fully loaded 300,000 DWT tanker can use the channel even at a low tide. After dredging, the tidal constraints described in section 2.4.2 will be removed.

iv) Add a buffer area next to the main channel to allow outbound tankers traveling in the channel to dodge the incoming inbound tankers, so that inbound and outbound tankers can use the one-way channel simultaneously. The cost for building a buffer area is generally much lower than widening the channel. For the RSOT, an existing anchorage named “Anchorage 4A”, which is located only 2 km from the main channel, can be readily used as the buffer; see Figure 8 for the illustration[6]. It can hold an outbound tanker even at a low tide, regardless of the tanker type. The outbound tanker takes 1 hour to navigate into, through and out of the buffer area, not counting the dwell time in the buffer. Inbound (laden) tankers are not allowed to use this buffer for safety reasons.

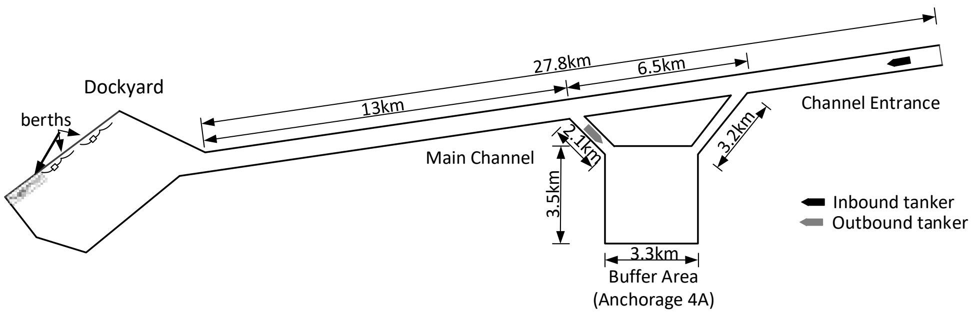

Figure 8. Proposed buffer location at the RSOT

For the last measure, tankers will follow a new service process as described in Figure 9, where the differences from the original process in Figure 5 are highlighted by the shaded blocks. Specifically, an inbound tanker is now allowed to set off from the anchorage when an outbound tanker is in the turning

[6] At present, the anchorage is mainly used for evacuation under extreme events (e.g. oil spill or explosion). Its utilization is near zero.

basin or the channel, given that the outbound tanker is able to dodge in the buffer before meeting the inbound one in the channel. Additionally, an outbound tanker is allowed to exit the berth when an inbound one is on its way to the channel under similar conditions. All the other conditions are the same as in Figure 5.

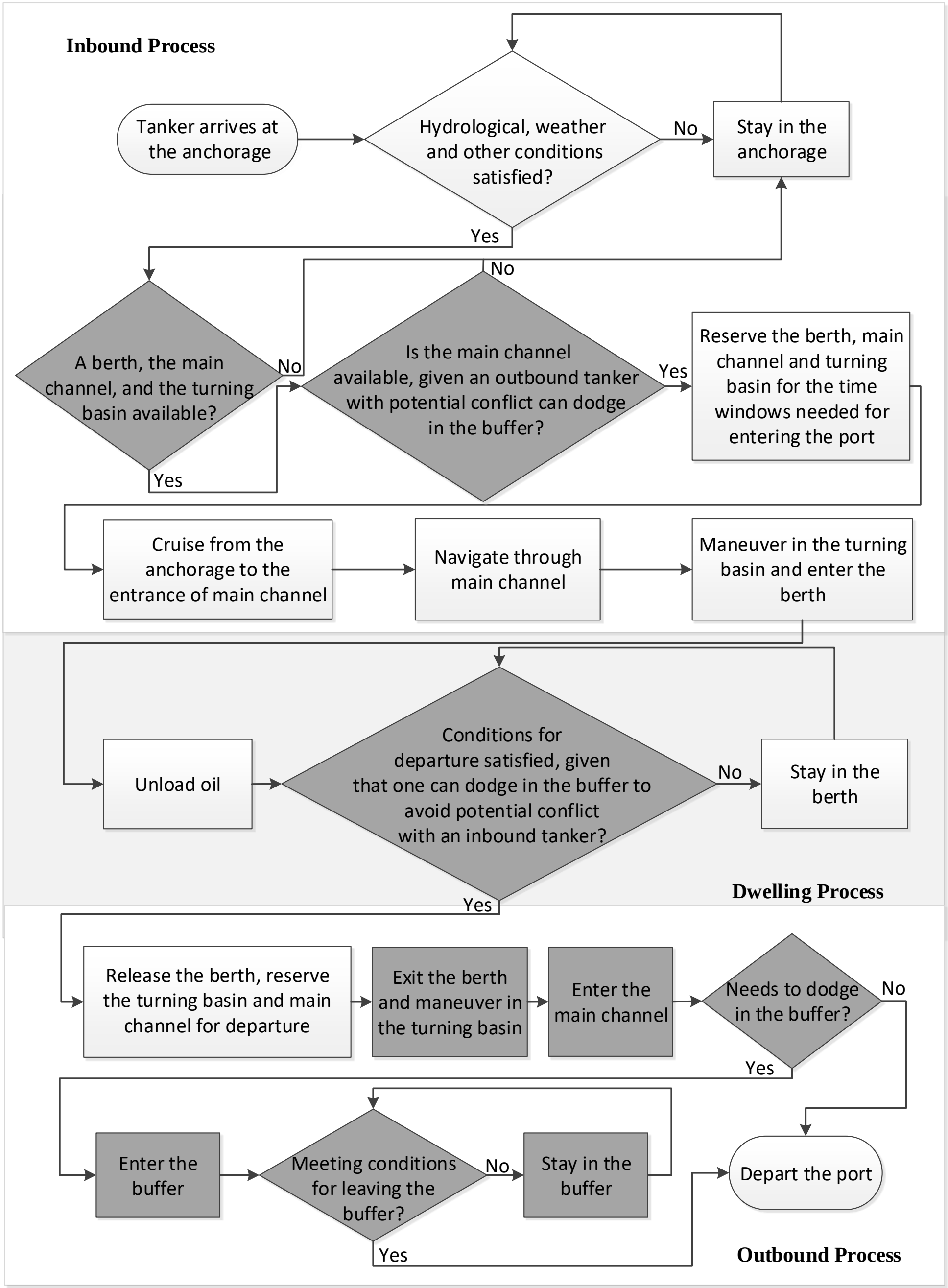

Figure 9. Flow chart for a tanker's service process with the buffer

Figure 10 illustrates the benefit that can be brought by the buffer using trajectories of two VLCCs, one outbound and the other inbound, under three scenarios: i) the present-day scenario plotted as blue solid curves; ii) the scenario with buffer plotted as green dashed curves; and iii) the scenario with a two-way channel plotted as orange dash-dot curves. The horizontal axis represents the time of a day and the vertical axis represents the space (not in scale). For simplicity, in this figure we assume the tidal constraint is always satisfied, and all the segment travel times are rounded to the nearest 0.5 hour. First note in the present-day scenario that an outbound tanker (see the blue double-line trajectory) departs a berth at 8:00, maneuvers in the turning basin for 1.5 hours, and exits the channel at 11:30. Thus, an inbound tanker (see the blue bold-line trajectory) can leave the anchorage no earlier than 10:00 to avoid conflict with the outbound one in the channel. It then enters the channel at 11:30, and arrives to the berth at 15:00 the earliest. Suppose it enters the same berth vacated by the outbound taker, then that berth will be idle for 7 hours.

Now consider the scenario where a buffer is deployed at the location described in Figure 8. The outbound tanker (the green double-line trajectory) can dodge in the buffer at 10:30; note that its trajectory before 10:30 is the same as in the present-day scenario (marked by blue double lines). It will then leave the channel at 12:00. Meanwhile, the inbound tanker (the green bold-line trajectory) can depart the anchorage as early as 8:00, so that it will arrive at the berth at 13:00. In this case, the berth idle time is reduced from 7 hours to 5 hours. Finally, if the channel is expanded to a two-way one, the outbound tanker's trajectory will be the same as on the present day (the blue double lines), while the inbound tanker can depart the anchorage as early as 6:00 (suppose another berth is available at that time) and arrive to the berth at 11:00. Here the berth idle time is further reduced to 3 hours. This illustration helps with the understanding of how the buffer can improve berth utilization, and how widening channel can produce even greater benefit (but also at a much higher cost) than adding the buffer.

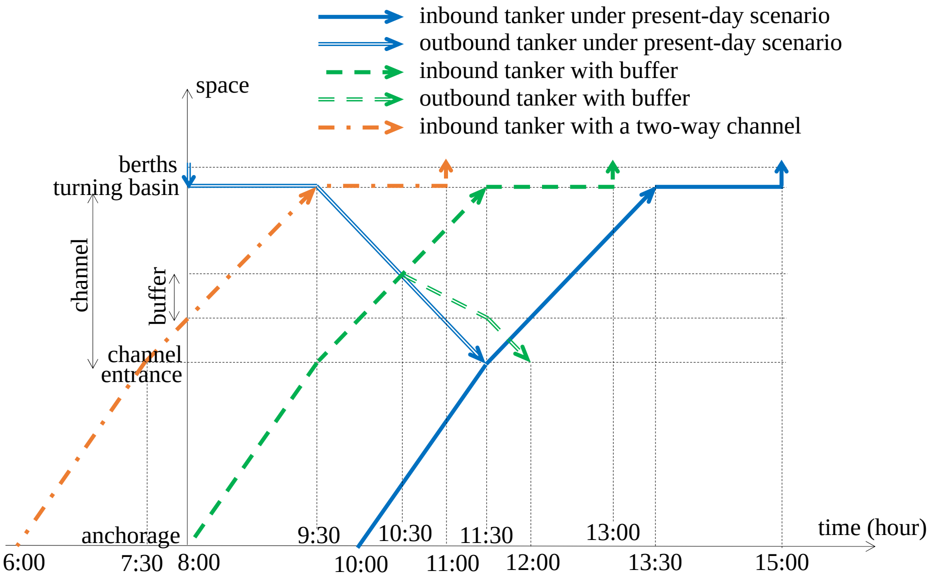

Figure 10. Typical outbound and inbound tanker trajectories under the present-day scenario, with a buffer, and with a two-way channel

4 Simulated oil throughputs and average tanker delays

Development and validation of the simulation models are briefly described in section 4.1. Simulated annual oil throughputs and average tanker delays over the next decade are compared for various operating scenarios in sections 4.2 and 4.3, respectively. Section 4.4 compares the outcomes between our simulation and a simulation program using a simplified tidal model similar to those assumed in the literature.

4.1 Simulation models

Two simulation programs were developed to model the port operations described in sections 2-3: one in ARENA 14.0 and the other in Matlab 2016b. They were developed in different ways: the ARENA program was coded in a discrete-event logic; while the Matlab program was discrete-time. Both programs were executed on a PC with Intel Core i7-8700 CPU @ 3.20 GHz and 16G RAM. The two programs validated each other, since the difference between the numerical results (e.g. the average tanker delays) generated from the two programs is negligible. Regrettably, we are not able to compare these results against the real data at the RSOT, since the latter are not available.

The Matlab program runs much faster than the ARENA program. Thus we use the former to examine numerical instances in the rest of the paper. We examine scenarios that feature 3-5 berths (i.e., adding 0, 1, or 2 berths to the present RSOT infrastructure) and four channel improvement options: do-nothing, (channel) widening, deepening, and adding-buffer.

4.2 Maximum annual throughputs

The maximum annual throughput of crude oil is defined as the *expected* maximum tonnage of oil that can be unloaded at the port per year given that the tankers' service level does not exceed a predefined threshold. Here the service level is measured by $\frac{AWT}{AST}$ (United Nations, 1985; Yang and Wei, 2004), where AWT denotes the average wait time per tanker, i.e. the average time duration from a tanker's arrival to the anchorage to its departure from the port, minus the average oil unloading time and the travel time to/from the berth; and AST denotes the average unloading time per tanker in a berth[7]. We examine the maximum oil throughput for three threshold values of $\frac{AWT}{AST}$: 1, 2, and 3. The maximum throughput is calculated by the following 3-step procedure.

Step 1. Initialize the total tanker arrival rate as $\lambda_0 = 200$ tankers/year. Simulate the port operations for 700 runs. Each run starts with a half-year warm-up period and then lasts for one year[8]. Calculate $X_0 \equiv \frac{AWT}{AST}$, where AWT and AST are averaged over the 700 runs. Let $i = 1$ and $\lambda_1 = 300$ tankers/year, then simulate and calculate $X_1 \equiv \frac{AWT}{AST}$ in the same way.

Step 2. If $|X_i - x| \leq \epsilon$, where x is the predefined service level threshold and ϵ is the tolerance (e.g., $\epsilon = 0.01$), then go to Step 3. Otherwise, let $i \leftarrow i + 1$ and calculate λ_i by linear interpolation: $\lambda_i = \frac{\lambda_{i-1}(x - X_{i-2}) + \lambda_{i-2}(X_{i-1} - x)}{X_{i-1} - X_{i-2}}$. Calculate $X_i \equiv \frac{AWT}{AST}$ for 700 simulation runs. Repeat Step 2.

Step 3. The maximum oil throughput is calculated as the mean total oil tonnage unloaded during the 1-year simulation period under the present tanker arrival rate λ_i.

The maximum throughput results for various service levels, berth numbers and infrastructure improvement measures are presented in Table 2. To examine the throughput gains resulting from adding berths and from each channel improvement measure separately, we also present in Table 3 the percentage throughput gains from each added berth (using the 3-berth case as the base) under each of the four channel improvement scenarios, and in Table 4 the percentage throughput gains from each channel improvement measure (using the do-nothing scenario as the base) under 3, 4, and 5 berths.

The results show that adding a new berth will significantly increase the maximum throughput. Regardless of the service level threshold used, a 4th berth brings a roughly 30% increase in the maximum throughput, and a 5th berth brings an additional 30%; see the 3rd row of Table 3. These percentages are greater than the percentage gains brought by any channel improvement measure alone (which are lower than 22%; see the 3rd row of Table 4). Hence, if the management agency's objective is to increase the crude oil throughput, adding more berths is the most effective measure. Even after the channel is deepened, widened, or a buffer is added, adding more berths can still bring 30% or more gains to the RSOT; see the 4th-6th rows of Table 3.

Among the three channel improvement measures, results show that deepening has almost no effect on the throughput under all the cases; see the 3rd, 6th and 9th columns of Table 4. A possible reason is that, with the oil loading distribution specified in our simulation, most VLCCs do not need to take high

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[7] In strong wind and high wave days, tankers dwelling in berths will stop their unloading operations. The resulting delay is counted as part of the wait time, not the unloading time.

[8] Our extensive simulation tests show that even under very congested cases (e.g., cases where $\frac{AWT}{AST} \approx 3$), the mean $\frac{AWT}{AST}$ over 700 simulation runs converges pretty well with a standard deviation less than 1% of the mean. For details on how the required number of simulation runs can be determined, please see Ross (2014).

tide to traverse the channel. This is manifested in Figure 11, where the probability density function of VLCC's oil loading distribution is plotted as the orange curve. The figure clearly shows that most VLCCs are on the left of the critical oil loading under which a VLCC can pass the channel even at the lowest tidal level (see the dashed vertical line on the left).

On the other hand, widening is the most effective, adding roughly 20% or more throughput to the terminal; see the 4th, 7th and 10th columns of Table 4. The performance of adding-buffer lies between deepening and widening, bringing approximately 15% throughput increase; see the 5th, 8th and 11th columns of Table 4. Still, adding-buffer can be more attractive to the management agency than channel widening thanks to its low construction cost.

Further note that the above findings are insensitive to the choice of the $\frac{AWT}{AST}$ threshold.

Table 2. Maximum annual throughputs (in million tons) under various scenarios

Threshold of $\frac{AWT}{AST}$		$\frac{AWT}{AST}=1$			$\frac{AWT}{AST}=2$			$\frac{AWT}{AST}=3$		
Number of berths		3	4	5	3	4	5	3	4	5
Channel improve-ment measures	Do-nothing	83.2	108.9	134.9	94.8	122.8	150.5	98.3	126.7	155.1
	Deepening	82.9	109.7	134.7	94.9	122.9	150.5	98.7	127.3	154.9
	Widening	100.8	136.8	169.2	113.4	151.9	186.2	117.9	156.3	191.6
	Adding-buffer	95.1	126.3	154.0	108.7	141.9	171.3	112.9	146.9	176.2

Table 3. Percentage throughput gains from each added berth

Threshold of $\frac{AWT}{AST}$		$\frac{AWT}{AST}=1$		$\frac{AWT}{AST}=2$		$\frac{AWT}{AST}=3$	
No. of *added* berth		4th berth	5th berth	4th berth	5th berth	4th berth	5th berth
Channel improve-ment measures	Do-nothing	31%	31%	30%	29%	29%	29%
	Deepening	32%	30%	29%	29%	29%	28%
	Widening	36%	32%	34%	30%	33%	30%
	Adding-buffer	33%	29%	31%	27%	30%	26%

Table 4. Percentage throughput gains from channel deepening, widening, and adding the buffer

Threshold of $\frac{AWT}{AST}$		$\frac{AWT}{AST}=1$			$\frac{AWT}{AST}=2$			$\frac{AWT}{AST}=3$		
Channel improvement measures		Deepen -ing	Widen-ing	Adding -buffer	Deepen -ing	Widen-ing	Adding -buffer	Deepen -ing	Widen-ing	Adding -buffer
Number of berths	3	-0.4%	21.2%	14.4%	0.1%	19.6%	14.7%	0.4%	19.9%	14.8%
	4	0.7%	25.6%	16.0%	0.0%	23.6%	15.5%	0.5%	23.4%	15.9%
	5	-0.1%	25.4%	14.1%	0.0%	23.8%	13.9%	-0.1%	23.5%	13.6%

4.3 Average tanker wait times

In addition to the port's maximum oil throughput, we are also interested in the average tanker wait times for a given tanker inflow. This is especially important for the RSOT due to the increasingly intensive competition between large oil terminals in the region (see again Figure 3). A tanker may avoid visiting a busy port if a nearby port has a lower wait time.

We simulate the average tanker wait times for a 10-year period from 2020 to 2029. The projected tanker arrival rates over the 10 years are obtained from a report of the RSOT (CCPDIWT, 2012). They are presented in Table 5. The wait time curves are plotted against year in Figures 12a and b for 100,000 DWT and 300,000 DWT tankers, respectively. Each figure presents 12 curves, among which, the black, red, and blue curves represent the results for 3, 4, and 5-berth ports, respectively; curves in solid, dashed, dotted, and dash-dot patterns represent the results for the do-nothing, deepening, widening, and adding-buffer scenarios, respectively.

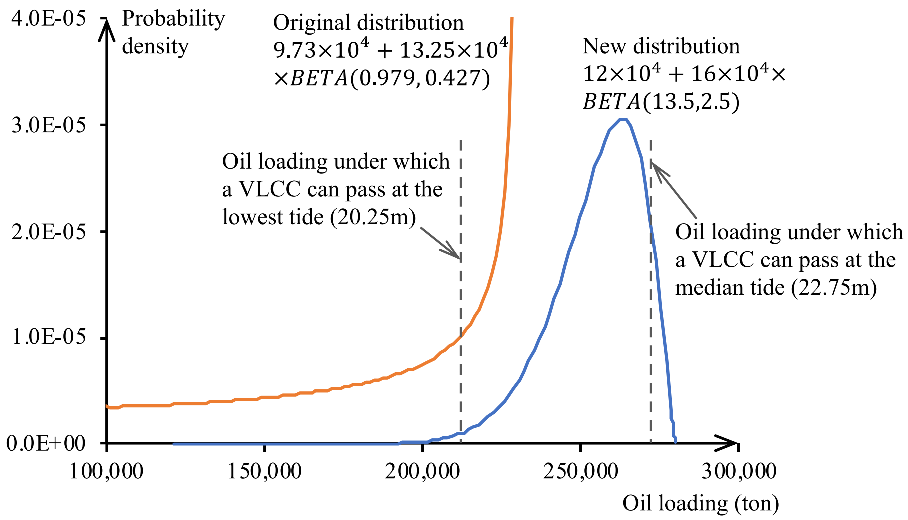
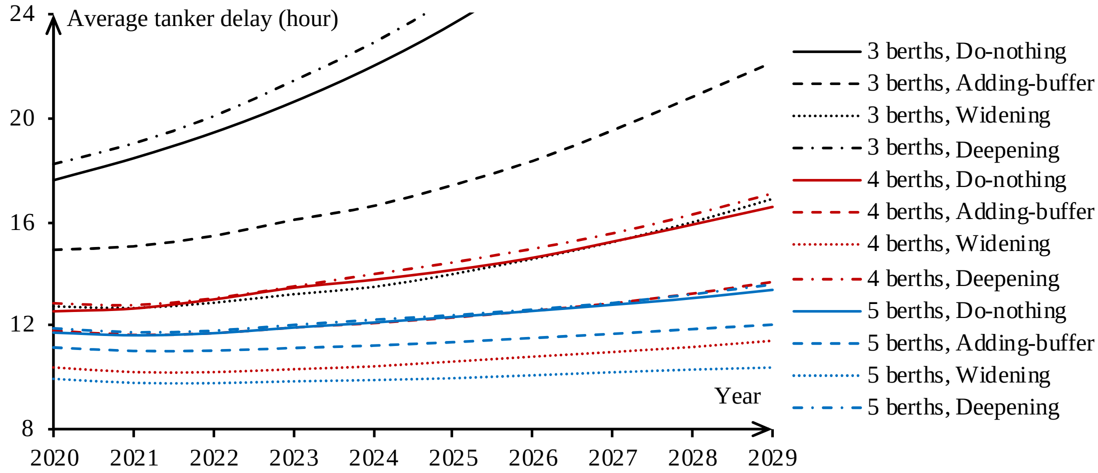


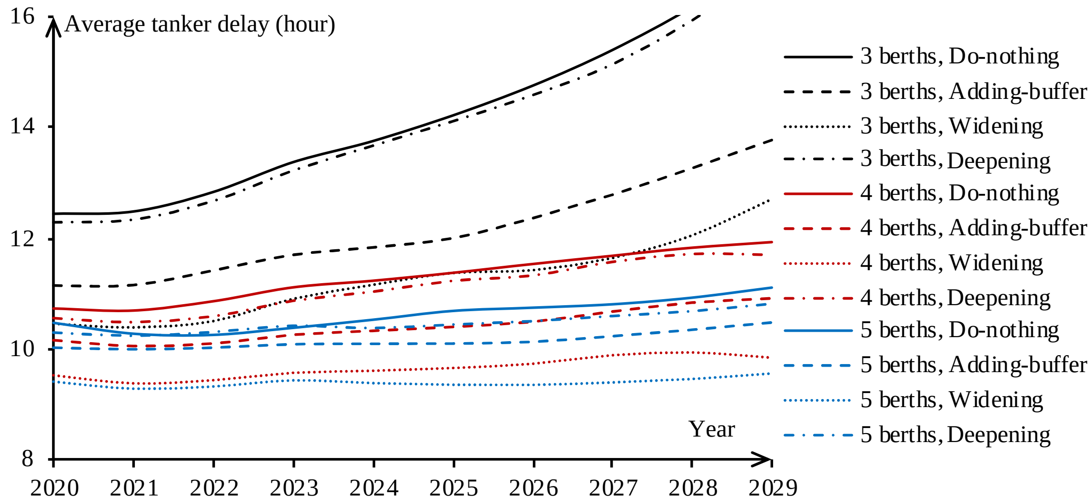
Figure 11. The original and new VLCC oil loading distributions

Table 5. Projected tanker arrival rates from 2020 to 2029

Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
Tanker arrival rate (tanker/year)	337	347	357	367	378	389	400	412	424	436



(a) 100,000 DWT tankers



(b) 300,000 DWT tankers

Figure 12. Simulated average tanker wait times for 2020-2029

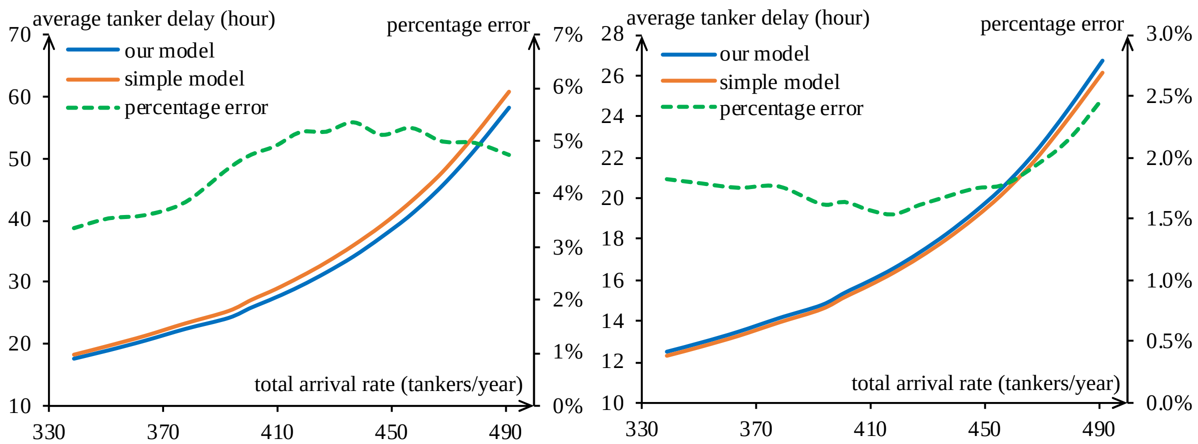
The figures show that, when more berths are added, the delays of both tanker types decrease, but the reduction for 100,000 DWT tankers is greater. This is because those smaller tankers suffer much larger delays when only 3 berths are available, due to the priority rules (h) and (i) in section 2.4.3. (This can also be seen by comparing Figures 12a and b.) In all the scenarios examined, wait time reductions brought by adding a 5th berth are much smaller than those brought by the 4th berth. This implies that adding a 5th berth may not be cost-effective given the predicted future tanker inflows in Table 5.

Regarding the channel improvement measures, widening and adding-buffer can reduce the delays for both tanker types, and the reduction is again much larger for smaller tankers. The effects of the two measures diminish as the berth number increases to 4 and 5. This is not surprising: the terminal becomes less congested after adding more berths, and thus the congestion-mitigation benefit brought by those channel improving measures is smaller. On the other hand, channel deepening only reduces the delays of VLCCs, while this measure actually increases the delays of smaller tankers. This is because deepening only benefits VLCCs by removing the tidal constraints on their navigation. The 100,000 DWT tankers will then suffer more delays since they are deprioritized. This result again indicates that deepening is not a good option for the RSOT, at least under the present tanker-processing priority rules.

4.4 Errors resulting from a simplified tidal model

To illustrate the necessity of using our realistic tidal model (section 2.4.2), the present section compares the simulated tanker delays that are produced when our tidal model and a simplified tidal model are used respectively. The simplified model assumes a fixed sinusoidal tidal pattern where a low tide always occurs at 6am (and a second low tide appears a little later than 6pm) of every day. All else are kept the same.

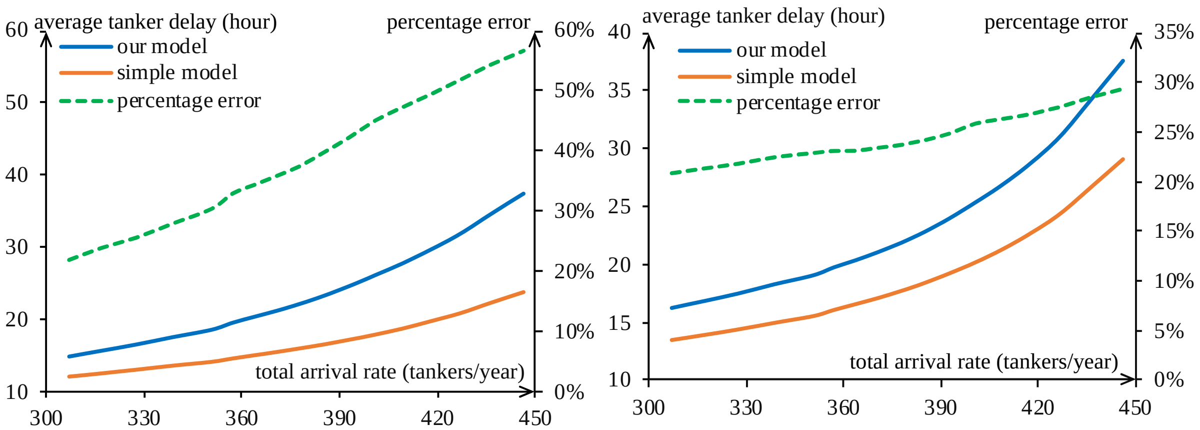
The comparison was first performed for the case of RSOT (with 3 berths and no channel improving measure) for various tanker arrival rates. Figures 13a and b plot the average delays for 100,000 DWT and 300,000 DWT tankers, respectively. The green dashed curve in each figure represents the percentage error between the simulated delays of the two programs. Results show that the error is below 6% for smaller tankers, and merely 2% for VLCCs. These small errors seem to imply that the simplified tidal model is fairly accurate. However, they are again due to the fact that most VLCCs in the simulation do not need to take high tide (see Figure 11). Hence, the impact of tidal constraints is small anyway. Further analysis unveils that these small errors are not general.



(a) 100,000 DWT tankers (b) 300,000 DWT tankers

Figure 13. Comparison between average tanker delays under the present oil loading distribution

We examine a new oil loading distribution for VLCCs, described by $12 \times 10^4 + 16 \times 10^4 \times BETA(13.5,2.5)$. Under this distribution, a significant portion of VLCCs must take high tide when traversing the channel; see the blue curve in Figure 11. We then find that the simplified tidal model would greatly underestimate the tanker delays, i.e., by over 20% for both tanker types; see Figures 14a and b. The new results reveal that for crude oil terminals where a significant portion of tankers are affected by tidal constraints, using simplified tidal models can produce unacceptably large errors. To attain better accuracy in simulation results, the realistic tidal model proposed in section 2.4.2 should be used instead.



(a) 100,000 DWT tankers (b) 300,000 DWT tankers

Figure 14. Comparison between average tanker delays under a new oil loading distribution

5 Optimal long-term infrastructure improvement plan

The construction and maintenance costs of the above infrastructure improving measures are very high. It would be uneconomical to implement a measure too early, i.e., when the tanker delays are not large yet. On the other hand, implementing a measure too late would incur great delay costs over the years before implementation. In this section, we examine how multiple types of infrastructure improvement activities can be optimally scheduled for minimizing the generalized system cost of the RSOT's operations over a long planning horizon. The generalized cost is defined as the sum of the terminal agency's cost (i.e. the infrastructure construction, operation and maintenance cost) and the user cost (including the tanker rental cost and oil holding cost). It is optimized under a given predicted demand over the planning horizon. Improvement options considered in this section include adding 1 or 2 berths, widening, and adding-buffer. Deepening is dropped here since it was shown in section 4 to be ineffective.

Detailed cost models are presented in section 5.1. Parameter values for the case of RSOT are furnished in section 5.2. The optimal improvement plan is developed in section 5.3. The planning horizon is set to 10 years, i.e. from 2020 to 2029.

5.1 Cost models

The generalized system cost, C, for a given planning period is defined as follows:

$$C = C_P + C_T + C_O \tag{5}$$

where C_P denotes the operation and maintenance costs for the port infrastructure, and the construction costs for infrastructure improvements if any; C_T the operation and rent cost for the tankers during their visits to the port; and C_O the holding cost for the crude oil carried by the tankers. All these cost variables are present values in the first year of the planning period. The three cost components are formulated in sections 5.1.1-5.1.3, respectively.

5.1.1 Costs for the port infrastructure

The C_P consists of six cost components as shown below:

$$C_P = C_{BO} + C_D + C_F + C_{BC} + C_W + C_{BU} \tag{6}$$

The cost components are defined as follows:

i) The maintenance and operation cost of the existing berths including the staff wages, C_{BO}.

$$C_{BO} = \sum_{j=1}^{T} \delta^{j-1} n_E \cdot c_{BM} = n_E c_{BM} \left(\frac{1-\delta^T}{1-\delta}\right) \quad (7)$$

where T denotes the planning period (in years); $\delta = \frac{1+i}{1+r}$ the annual discount factor (i and r denote the annual inflation rate and the annual depreciation or interest rate, respectively; $r > i$ so $\delta < 1$); n_E the number of berths at the beginning of the planning period; and c_{BM} the annual maintenance, operation, and staff wage cost per berth. We assume the total maintenance, operation, and staff wage cost is proportional to the number of berths.

ii) The routine maintenance cost for the main channel (i.e. cost for the routine dredging activities), C_D.

$$C_D = \sum_{j=1}^{T} \delta^{j-1} c_{CM} = c_{CM} \left(\frac{1-\delta^T}{1-\delta}\right) \quad (8)$$

where c_{CM} denotes the amortized cost per year for routine channel dredging activities.

iii) The fuel cost for oil unloading operations, C_F.

$$C_F = \sum_{j=1}^{T} \delta^{j-1} c_{F0} L_j \quad (9)$$

where c_{F0} denotes the unit fuel cost for unloading a ton of oil, and L_j year j's crude oil throughput.

iv) The construction and maintenance cost of added berths, C_{BC}.

$$C_{BC} = \sum_{k=1}^{n_N} \left(\delta^{t_k-1} c_{BC,k} + \sum_{j=t_k+t_{BC}}^{T} \delta^{j-1} c_{BM}\right) = \sum_{k=1}^{n_N} \left(\delta^{t_k-1} c_{BC,k}\right) + n_N c_{BM} \left(\frac{\delta^{t_k+t_{BC}-1} - \delta^T}{1-\delta}\right) \quad (10)$$

where n_N denotes the number of new berths constructed during the planning period; $c_{BC,k}$ the construction cost of the k-th new berth ($k = 1,2,\dots,n_N$); t_k the year when the k-th new berth's construction starts; and t_{BC} the construction period.

v) The cost for widening the main channel and the ensuing cost increase in channel maintenance, C_W.

$$C_W = \delta^{t_W-1} c_{W0} D + \sum_{j=1}^{T-t_W} \delta^{t_W+j-1} c'_{CM} = \delta^{t_W-1} c_{W0} D + c'_{CM} \left(\frac{\delta^{t_W} - \delta^T}{1-\delta}\right) \quad (11)$$

where c_{W0} denotes the unit cost per cubic meter of seabed excavation; D the amount of excavation in cubic meters; t_W the year of widening; and c'_{CM} the *added* cost for routine dredging maintenance after widening, amortized to each year.

vi) The construction and maintenance cost of the buffer area, C_{BU}.

$$C_{BU} = \delta^{t_{BU}-1} c_{BUC} + c_{BUM} \left(\frac{\delta^{t_{BU}+t_{BUC}-1} - \delta^T}{1-\delta}\right) \quad (12)$$

where t_{BU} and t_{BUC} denote the start year and duration of construction, respectively; and c_{BUC} and c_{BUM} the buffer's construction cost and annual maintenance and operation cost, respectively.

Note that (10-12) are applicable only if more berths are added, the channel is widened, and the buffer is added, respectively.

5.1.2 Costs for the tankers

A tanker's operation and rent cost at the port covers the period from its arrival at the anchorage to its departure from the main channel after unloading. The total cost for all the tankers served during T is calculated as follows:

$$C_T = \sum_{j=1}^{T} \delta^{j-1} \left(c_{D1} W_{D1,j} + c_{N1} W_{N1,j} + c_{D3} W_{D3,j} + c_{N3} W_{N3,j}\right) \quad (13)$$

where $W_{D1,j}$ and $W_{D3,j}$ are the total times that 100,000 DWT and 300,000 DWT tankers, respectively, spend on dwelling (in the anchorages and the berths) in year j; $W_{N1,j}$ and $W_{N3,j}$ the total times that 100,000 DWT and 300,000 DWT tankers, respectively, spend on navigation (from an anchorage to a berth and from a berth to the channel entrance) in year j. These times are outputs from the simulation model. The c_{D1}, c_{N1}, c_{D3}, and c_{N3} are the associated tanker operation (including fuel) and rent cost per hour.

5.1.3 *Costs for the oil*

Finally, the total holding cost of the crude oil is calculated by:

$$C_O = \sum_{j=1}^{T} \delta^{j-1} c_{O0}\left(V_{3,j} + V_{1,j}\right) \quad (14)$$

where c_{O0} denotes the unit holding cost per hour per ton of oil; $V_{3,j}$ and $V_{1,j}$ are the cumulative ton-hours of oil holding for 300,000 DWT and 100,000 DWT tankers in year j, respectively. Here we only consider the holding cost of oil when it is stored in the tanker. The holding cost after the oil is pumped into the onshore storage tanks are not included. Thus, the number of oil holding ton-hours for a tanker is equal to its oil loading multiplied by the duration from its arrival at the anchorage to the start of unloading at a berth, plus the ton-hours of holding during the unloading process. The latter is equal to the tanker's oil loading multiplied by half of the unloading time. For interruptions of the unloading process caused by extreme weather, the remaining oil in the tanker is multiplied by the dwelling hours under extreme weather and added to the holding cost. The holding cost rate $c_{O0} = \frac{S_0 r}{365\times 24}$, where S_0 is the present oil price per ton, and r is the annual interest rate.[9]

5.2 Parameter values

For the case of RSOT, we set $T = 10$ years. The inflation rate is set to the average of the inflation rates in China from 2008 to 2017; i.e., $i = \sqrt[10]{\prod_{j=2008}^{2017}(1+i_j)} - 1 = 2.91\%$, where i_j represents the inflation rate of year j (NBS, 2008-2017). The depreciation rate r is set to 8% (SDPC, 2008). The remaining parameter values are obtained from the materials provided by the RSOT (CCPDIWT, 2011, 2012) and a study of a similar neighboring crude oil terminal (Feng et al., 2015). These parameter values are summarized in Table 6.

We assume that, if the RSOT decides to widen the channel or add a buffer, then these improvement measures will be implemented in year 1; i.e., $t_W = 1$ and $t_{BU} = 1$ if applicable. The annual tanker inflows for the future years, L_j $(j = 1,2,\ldots,T)$, are given in Table 5.

Table 6. Parameter values

Parameter	Value	Parameter	Value
n_E	2	c_{BM}	5,860,000 CNY/berth [#]
t_D	5 years	c_{CM}	20,000,000 CNY
c_{F0}	0.2128 CNY/ton	$c_{BC,1}$	585,330,000 CNY
$c_{BC,2}$	585,330,000 CNY	t_{BC}	3 years
c_{D1}	7538 CNY/hour	c_{D3}	12441 CNY/hour
c_{N1}	9633 CNY/hour	c_{N3}	16604 CNY/hour
S_0	5000 CNY/ton	c_{W0}	37.36 CNY/m^3
D	16,575,000 tons	c'_{CM}	10,000,000 CNY
c_{BUC}	10,000,000 CNY [†]	c_{BUM}	0 [†]
t_{BUC}	0 [‡]		

[#] Including the wage cost of 4,260,000 CNY and the maintenance and operation cost of 1,600,000 CNY.
[†] These parameters are estimated by assuming that the present Anchorage 4A (see Figure 8) is used as the buffer. Hence the cost is much lower than the cost for building a new buffer.

5.3 Optimal long-term improvement plan

We optimize the number of new berths to be constructed, n_N $(0 \le n_N \le 2)$, their construction years, t_k $(1 \le t_k \le 10, k = 1,\ldots,n_N)$, and whether widening or adding-buffer will be implemented (in year 1). This is done by exhaustive search since the solution space is small. Specifically, the solution space is:

[9] In the interest of brevity, here we assume that the future oil price will grow with a constant inflation rate i. In reality, oil price often exhibits large fluctuations over time. Our cost models can be modified to incorporate more accurate predictions of future oil prices, should those become available.

$$\Omega \equiv (\{n_N = 0\} \cup \{n_N = 1, 1 \le t_1 \le 7\} \cup \{n_N = 2, 1 \le t_1 \le t_2 \le 7\}) \times \{\text{Do-nothing, Widening, Adding-buffer}\}$$

where × indicates the Cartesian product of two sets. Note the construction period of a berth is 3 years, thus the latest time a berth can start its construction is year 7 (i.e. the year 2026). There are totally $\|\Omega\| = (1 + 7 + 28) \times 3 = 108$ feasible plans to be explored via simulation.

By comparing the generalized costs of all the 108 scenarios, we find the optimal improvement plan involves adding the buffer in year 1 and not adding any new berths. The associated minimum generalized cost over the 10-year period is 2.733 billion CNY, as shown in the 4th column of Table 7. The table also shows the lowest generalized cost under each of the three channel improvement options with 3 or 4 berths. The numbers unveil that, whether widening or adding-buffer is implemented or not, adding a 4th berth will always increase the generalized cost by over 15%. Moreover, the optimal year for building the 4th berth is always 2026, i.e., the latest possible year for building this berth. This indicates that, given the projected tanker flows in Table 5, it is uneconomic to build the 4th berth in the next 10 years, albeit adding this berth would significantly reduce the tanker delays (see again Figures 12a and b). Similarly, adding a 5th berth would be even less cost-effective, and the result is not shown in the table for simplicity. When no berth is added, widening yields a generalized cost 19% greater than the status quo (Do-nothing), while adding-buffer saves by 3.4%.

Table 7. Minimum generalized costs for different channel improvement measures with 3 or 4 berths

Number of berths	3			4		
Channel improvement	Do-nothing	Widening	Adding-buffer	Do-nothing	Widening	Adding-buffer
Minimum generalized cost (million CNY)	2,923	3,468	**2,825**	3,357	3,906	3,259

To examine whether the optimal plan is robust to changes in predicted demand, we repeat the optimization for two more cases, a conservative one with an annual demand growth rate of 1.5%, and an aggressive one with an annual demand growth rate of 6% (note that the annual growth rate in Table 5 is 2.9%). Predicted tanker flows for the two cases are shown in Table 8. The generalized costs for plan options with 3 or 4 berths are presented in Table 9. Plan options with 5 berths are omitted because they (again) yield much greater costs. Table 9 shows that for both cases, adding a buffer without adding more berths is again the minimum cost plan. The cost savings as compared to the status quo are 3% and 8%, respectively. These results manifest the robustness of the optimal infrastructure improvement plan.

Table 8. Projected tanker arrival rates from 2020 to 2029 for the conservative and aggressive cases

Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
The conservative case										
Tanker arrival rate (tanker/year)	337	342	347	352	358	363	368	374	380	385
The aggressive case										
Tanker arrival rate (tanker/year)	337	357	379	401	425	451	478	507	537	569

Table 9. Minimum generalized costs for different channel improvement measures with 3 or 4 berths for the conservative and aggressive cases

Number of berths	3			4		
Channel improvement	Do-nothing	Widening	Adding-buffer	Do-nothing	Widening	Adding-buffer
The conservative case						
Minimum generalized cost (million CNY)	2,751	3,313	**2,667**	3,195	3,763	3,107
The aggressive case						
Minimum generalized cost (million CNY)	3,527	3,845	**3,240**	3,825	4,286	3,666

6 Conclusions

We developed two simulation models for oil tankers' navigation and unloading operations at the RSOT crude oil terminal, which accounts for a number of features that are unique and important to the operations of large-scale crude oil terminals, including the single one-way channel, navigation rules for safety, and realistic tidal dynamics. Many of these features have not been properly addressed in the literature. The models were used to examine the effects on the terminal's annual throughput, tanker delays and generalized cost that come from four types of seaside infrastructure improvements: adding berths, widening the channel, deepening the channel, and adding a buffer. Our main findings are summarized as follows:

(1) Adding berths can significantly increase the throughput and reduce the tanker delays. However, this measure may not be economically efficient due to the high construction cost.

(2) Channel deepening has almost no benefit.[10]

(3) Adding a buffer to allow outbound tankers to give way to inbound ones in the one-way channel proves to be a cost-effective measure. Despite its low cost, this measure can produce fairly large throughput gains (see again Table 4) and tanker delay reductions (see again Figures 12a and b). It is further shown that the minimum-cost infrastructure improvement plan for the next decade at the RSOT only requires to build such a buffer.

To be sure, the above findings are obtained for the RSOT case only. For example, the plan featuring the use of buffer, as shown in Tables 7 and 9, becomes optimal in part due to the very small construction cost of the buffer. Still, we believe that above findings have practical implications in a broader scope. Even in cases where no existing buffer is available, constructing a new buffer undeniably requires much less seabed excavation as compared to channel widening, and thus enjoys a much lower cost. The key insight our paper conveys is that this novel, cost-effective channel improvement measure holds much promise for ports where a one-way channel is the bottleneck.

Admittedly, the outbound tankers' operations in the buffer are simplified in this paper, since no real instance of this kind of buffers has been found in practice to our best knowledge. Still, the cost advantage of the buffer is evident. We are currently formulating practical navigation rules and safety constraints for buffer operations, and seeking approvals from the maritime authority for real-world implementation.

We will also seek additional data sets on real tanker operations at crude oil terminals and use them for validating and refining our simulation models. The validated models can be applied to study a number of crude oil terminal operation questions beyond the scope of the present paper. For example, the simulation-based analysis can be simply extended to examine the optimal seaside infrastructure improvement plan of the RSOT considering different planning periods and multifarious uncertainties (e.g., the uncertainties in the international and domestic economic environments). More robust plans can thus be derived. The models can be further modified to examine crude oil terminals with different layouts and navigation priority rules (e.g., outbound tankers first, smaller tankers first, tankers with higher demurrage rates first, or some mixed priority strategies). Built upon the present models, we also plan to further examine tanker operations at a set of neighboring terminals, which would allow us to explore the terminal competitions, and find out a port's optimal infrastructure improvement plan in response to port competition. Real-time scheduling of tankers' inbound and outbound activities is another direction for future research. This potential extension will explore the real-time allocation of both the channel and berth resources to tankers in a complex crude oil terminal under a highly stochastic operating environment.

[10] Even if a significant portion of tankers need to take high tides, a deepened channel will benefit those large tankers only, but will make the smaller tankers worse off due to the priority rules. The overall benefits of deepening are thus likely small.

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