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Review

Onshore ballast water treatment: A viable option for major ports

Newton Narciso Pereira *, Hernani Luiz Brinati

Department of Naval Architecture and Ocean Engineering Escola Politécnica (EP), Universidade de São Paulo (USP), Av. Luciano Gualberto, 2230, 05508-030 São Paulo, SP, Brazil

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ABSTRACT

Ballast water treatment consists of the elimination of exotic species. Currently, the development of alternative methods for this process is directed toward treatment onboard ships. However, we present onshore treatment as a viable alternative for ballast water treatment. We investigated onshore treatment in two iron ore ports with movement capacities of 25 and 90 million tons annually (Mta) that receive 7.5 and 25 million cubic meters annually (Mm^3) of ballast water, respectively. Discrete event simulation was used as the method of analysis, considering the processes of arrival, berthing, ship loading and capture and treatment of ballast water. We analyzed data from 71 ships operating in these ports to validate our simulation model. We were able to demonstrate that onshore treatment does not impact the cargo capacity, occupation rate or average queuing time of ships at these ports. We concluded that implementation of onshore ballast water treatment may be practicable in ports that receive high volumes of ballast water.

1. Introduction

Maritime navigation is considered to be the greatest dissemination vector for exotic species through the ballast water of ships (Minton et al., 2005; Ruiz et al., 1997). To control this problem, in 1997, the International Maritime Organization (IMO) established that all ships have to perform a mid-ocean ballast exchange. The efficacy of this method varies between 95% and 99% (Gray et al., 2007). However, its application is questioned in terms of ship operational security (Cohen, 1998; Endresen et al., 2004; Burkholder et al., 2007).

Onboard ballast water treatment is also a feasible possibility. There are currently 23 treatment systems homologated by the IMO to meet IMO-D2 standards, which employ techniques such as filtration, UV radiation, separation through hydrocyclones and biocides (Register, 2007). However, these systems cannot be applied to all ships due to great limitations of space on board and power and retrofitting capacities (Kazumi, 2007). In addition, the installation costs of these systems may reach US$2 million (Register, 2010). Furthermore, since 2009, the states of California, New York and Michigan have studied a 100-fold increase in the restriction of treatment efficacy in relation to IMO-D2. These measures are expected to come into effect by 2013. Analysis of these 60 available systems, considering those ratified by the IMO, showed that none of them complies with the efficacy standards of these states (Dobroski et al., 2011).

It is also possible to treat ballast water in port (Quarantine and AQISa, 1993), which consists of capturing, storing and treating ballast water onshore. This procedure is similar to that available at the Valdez Terminal, Alaska, which was designed to treat 33 million gallons of ballast water daily (Tsolaki and Diamadopoulos, 2010). However, the treatment applied does not eliminate invasive species; it only separates the oil mixed with the ballast water. Few studies on this alternative have been conducted (Cohen, 1998). The first study was led by Pollutech in 1992, and in 1993, this alternative was considered for Australian ports (Cohen, 1998; Quarantine and AQISa, 1993); other studies were also conducted for ports located in California (of Port Authorities, 2000). In 2007 and 2008, the port of Milwaukee evaluated the implementation of a new onshore treatment station to serve 85 ships annually ranging from 8000 DWT to 20000 DWT (Brown and Caldwell, 2007). Recently, the Ecological Processes and Effects Committee Augmented for Ballast Water in the United States has been developing studies addressing onshore treatment as an alternative for invasive species management.

One advantage of onshore treatment compared to onboard treatment is that local authorities can operate and conserve the installations and execute routine monitoring to analyze the efficacy of the system (Cohen and Foster, 2000). Additionally, onshore treatment provides better economies of scale in terms of construction and operation when compared to the systems installed in ships to treat the same volume of ballast water (Cohen and Foster, 2000; Council, 1996).

The disadvantages are the requirement for drainage in ports and for connections between the treatment stations and all berths. Each ship needs to modify its ballast water pumping system in the event

* Corresponding author. Tel.: +55 30911724.
E-mail addresses: newton.pereira@usp.br (N.N. Pereira), hlbrinat@usp.br (H.L. Brinati).

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of the impossibility of using pipelines to connect ballast tanks (Quarantine and AQISa, 1993). Delays in transportation may occur if the ballast water volume of ships exceeds the capacity of the treatment system (Quarantine and AQISa, 1993; of Port Authorities, 2000). This can be a viable option for small ports that receive few ships or for old ships that cannot be modified (Agency, 2002).

Based on these positive and negative considerations about onshore treatment, we studied the operational impact of onshore treatment on iron ore ports that receive volumes of ballast water greater than 5.5 million m^3 annually. We developed a discrete events simulation model referred to as TRANSBALLAST. The models main characteristic is its consideration of the randomness of ship operation in ports. This model represents ship arrival, berth operation, loading and ballast water transference to tanks and the onshore treatment station. Two ports were selected for analysis of this treatment alternative.

The Port of Tubarão (Port 1) moves approximately 90 MTA and receives ships ranging from 40,000 DWT to 400,000 DWT that discharge approximately 25 Mm^3 of ballast water annually. The Port of Sepetiba (Port 2) moves approximately 25 MTA and receives ships ranging from 60,000 to 200,000 DWT that discharge approximately 7.5 Mm^3 of ballast water annually. We used the data available at the websites of these ports to validate the simulation results. The model generated 596 ships for Port 1 and 162 ships for Port 2 in its simulations. We analyzed the impact of Very Large Ore Carrier (VLOC) ships of 400,000 DWT discharging ballast water in Port 1. In both cases, we observed that onshore ballast water treatments do not impact the loading of ships. This model may help in sizing onshore treatment stations for several types of ports. This study is relevant, as there is no conclusive solution for the elimination of organisms present in ballast water. As there are few countries exporting commodities such as iron ore that receive ships that are greater than 200,000 DWT in ballast condition, a viable alternative is to provide these ports with onshore treatment facilities. Ore carriers usually operate in specific routes with little alternation, e.g., Brazil - Asia, and these vessels do not carry cargo on the majority of their return voyages.

The ore carriers that are now being manufactured have recently increased in size. In 2011, the Vale Brasil vessel was released; it was the first of a series of vessels with a capacity of 400,000 DWT for carrying iron ore, and these ships transport approximately 120,000 m^3 of ballast water per voyage. These vessels are expected to undertake five voyages per year, transporting approximately 600,000 m^3 of ballast water annually. Based on these data, we suggest onshore treatment as the most viable option for these terminals to reduce the impact of the invasion of organisms present in ballast water.

2. Study area

The Port of Tubarão is located in Vitória – ES and has three berths. Berth 1 is split into North and South areas and can receive two vessels simultaneously, but it is limited to ships of 200,000 DWT or less. Berth 2 receives ships with capacities higher than 300,000 DWT.

The Port of Sepetiba is located in Rio de Janeiro. It is a port complex that attends several types of vessels. Iron ore is handled by two companies in two distinct terminals. This study considers one terminal that operates with one berth and receives ships of up to 200,000 DWT.

3. Modeling and methodology

The Discrete Event Simulation model developed in this study was called TRANSBALLAST. The model type is input and output, where the input data are incorporated to obtain specific outputs. The computational model concept was berth operation (berthing, ship loading and unberthing). The onshore ballast water treatment modeling consisted of collecting the ballast water in the berth, storing the water in tanks, transferring it to treatment stations and then loading the ships (Fig. 1). We considered the rate of ballast water transference to tanks to be equal to the rate of the ballast water pumps on ships.

In the simulation model, we assumed that there is always cargo in the port for ship loading. Conceptually, the ship only berths when there is iron ore to load in the yard. The yard operations and the receiving of iron ore were not considered in the simulation. The simulation model took into account the following variables:

1. the transportation demand of the port in tons;
2. the classes of ships berthing in the ports are Panamax, Capesize, Very Large Cape & Very Large Crude Carrier – VLOC;
3. ship navigation in the access channel;
4. berthing and unberthing operations, as the ships always arrive with ballast in low draught and depart the ports loaded (some depend on the amplitude of the tide in function of the draught);
5. berthing time, which consists of ship mooring maneuvers;
6. time before operation (concerning documentation);
7. connection of pipelines, opening of holds and post-operation, which consists of disconnecting the pipelines, closing the holds and trim, in addition to unberthing operations estimated in hours;
8. ship loading rate in tons/h, for which an average loading rate is assumed;
9. unballasting as a function of the ships ballast water pumps;
10. treatment rate in m^3/h;
11. storage capacity of the ballast water tanks in m^3.

One probabilistic distribution was attributed to each variable to represent the random processes of the system. The arrival of the ships is ruled by an exponential distribution expo α, which is a distribution represented by parameter β. A triangular distribution was applied to the treatment rates, loading and times of operation. This triangular operation is a continuous probability distribution that has a minimum value of a, a maximum value of b and mode of c, which are specified as real numbers with $a < m < b$.

The TRANSBALLAST model was developed to simulate the behavior of the port and to provide the following answers:

1. annual transportation demand attended in tons;
2. unballasted volume in m^3;
3. time and average queue number of ships;
4. berth occupation rate and lay days and the port services level.

For the treatment system, the number of tanks in m^3 and the ballast water treatment rate in m^3/h are indicated, and the number of stops for loading is quantified as a function of onshore ballast water treatment, which may impact the ports operability.

All of the simulations considered 10 replications with a 10-year time span. The replications guarantee adherence of the results within a certain confidence interval (Chen et al., 1997).

3.1. Unballasting rate $\times$ship loading

We created a specific logic to represent the unballasting process and ship loading. We observed that when a ship berths in the port, the unballasting process is initiated. The capacity of the ballast pumps is usually lower than the ship loading rate. Ship loading consists of distributing the product uniformly inside the hold. For

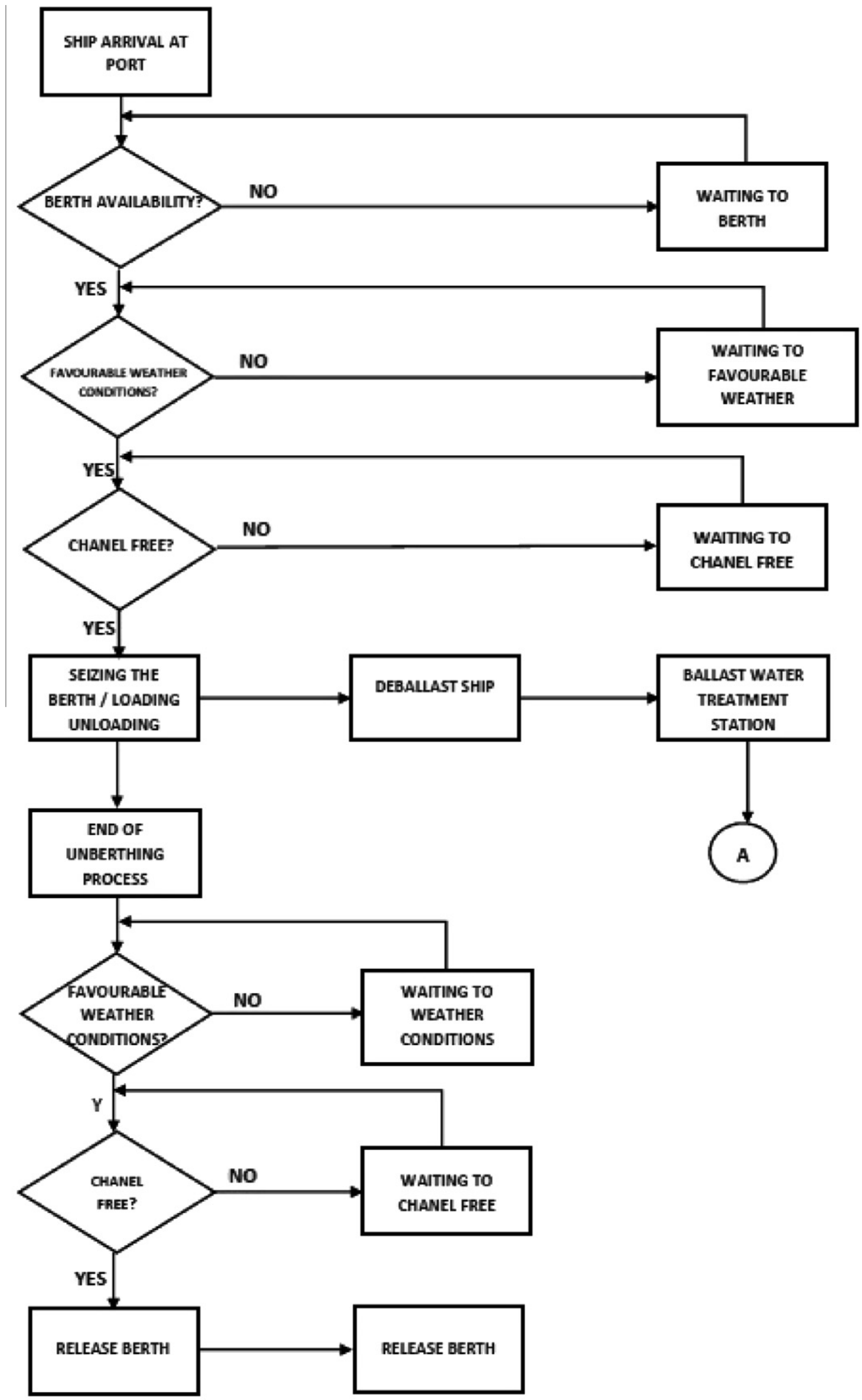

Fig. 1. Graphic scheme of the conceptual model for the onshore treatment station.

this purpose, it is necessary to load the same hold at least twice during the complete ship loading cycle. After loading of 50% of the hold, the shiploader is moved to another hold, and the process is repeated until the loading of the first cargo is completed in all of the holds. In this way, the ballast water tank is emptied, and the process continues in the next hold (Fig. 2).

The loading process is, thus, associated with the process of unballasting the ship. As a function of the loading rate (tons/h) for a certain ship class and the unballasting flow (m^3/h), hold changing only occurs when both processes reach their end. It is therefore possible to compute the time during which the ship loading system is stopped because of the unballasting process.

3.2. Data collection

We gathered data related to ship arrivals, waiting and the time of ship operations from the websites of mining companies. The data collection was concentrated in the period of September to November of 2008 for the Port of Tubarão and March and April of 2009 for the Port of Sepetiba.

The data were available in the on-line ship programming section. Each company presented its data in a different way, and some information related to berthing and unberthing times were not complete. The data were selected in the most complete way possible.

For Port 1, data from 56 ships were analyzed, while 15 ships berthed during the study period in Port 2. Based on these data, we determined the Estimated Time in Queue (ETQ), subtracting the Estimated Time in Berth (ETB) from the Estimated Time of Arrival (ETA). The Estimated Time of Port Operation (ETPO) was calculated by subtracting the Estimated Time of Departure (ETD) from the ETB. The Estimated Time of Ship Stay (ETSS) was calculated by subtracting the ETD from the ETA.

4. Premises of the simulation

The premises considered the inputs for other navigation operations in the channel, berthing, operation, unberthing, unballasting and ballast water treatment. Initially, the classes of ships that use these ports were identified in the following (Table 1).

The tide window input is not a restriction for berthing because the ships berth in ballast condition. During departure, the following classes of ships unberth only in tide amplitude to improve their draught: Class 6 and beyond for Port 1 and Class 5 and beyond for Port 2. The capacity of ballast water tanks is an input parameter for the model. The ballast water treatment rate was established to meet the ballast water volume discharged in the port annually. The distribution of the ships berthing in the ports is presented in Table 2. The classes of ships are randomly sorted by the simulation model.

Based on the collected data, the average productivity of the berths was defined. In 2005, we analyzed the ballast water reports from 560 ships that berthed in Port 1. We verified that the volume of ballast water on board each ship was approximately 30% of the DWT. This value can reach 40% of the DWT (Endresen et al., 2004; Cohen, 1998). The average flow of the ballast water pumps was identified as a function of the ships classes and ranged from 300 m^3/h to 5000 (m^3/h). However, the number of ships with high flows is reduced (Dobroski et al., 2010; Cohen, 1998).

5. Results of the simulations

To proceed with the simulation, it was necessary to validate the developed model. In the validation process, we checked whether the model presented similar results to the actual situation at the port when operating without the onshore treatment system.

As the model already considered the proposed treatment system, we assumed for validation that the receiving tank and ballast water treatment are not restrictions for port operation. The valida-

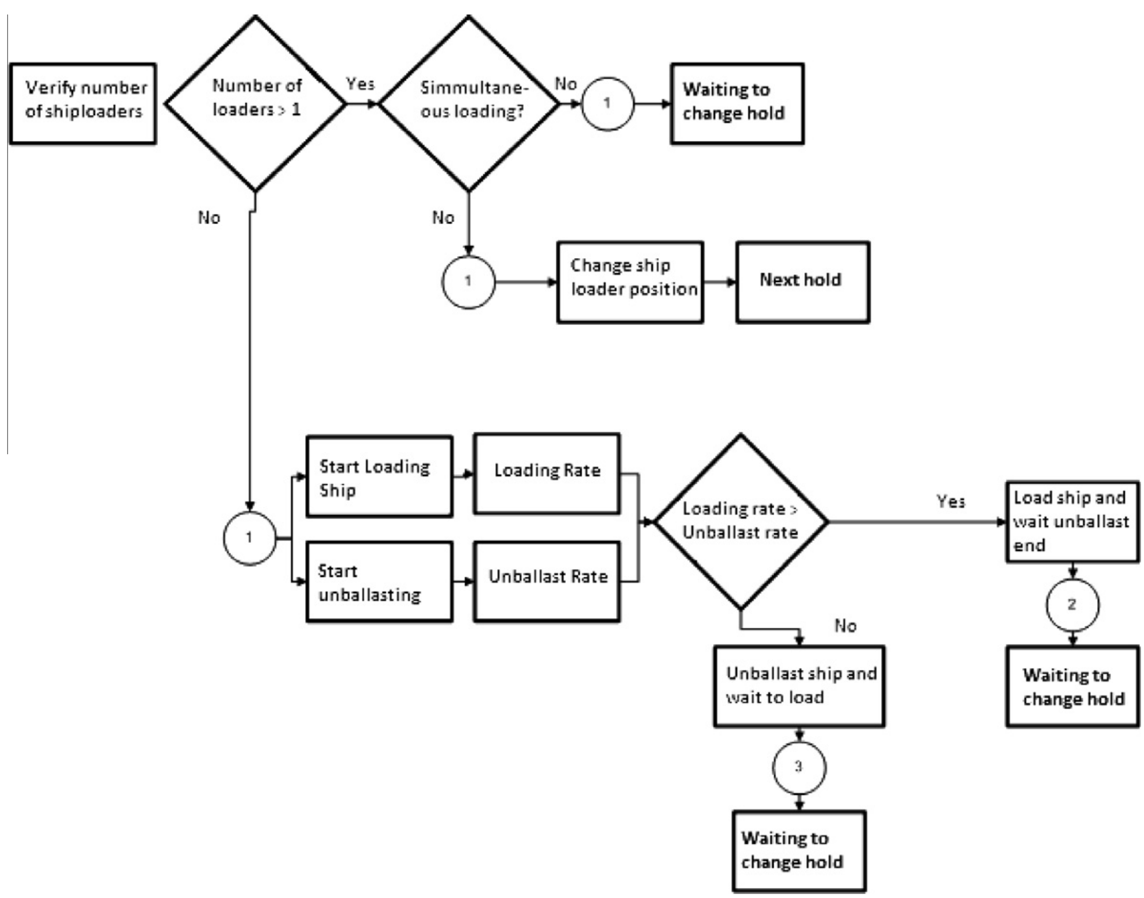

Fig. 2. Scheme of the ship loading and unballasting process.

Table 1
DWT of the ships as a function of their classes.

Classes	Ship 1	Ship 2	Ship 3	Ship 4	Ship 5	Ship 6	Ship 7
DWT Min	40,000	60,000	80,000	140,000	180,000	220,000	350,000
DWT Med	50,000	70,000	90,000	160,000	200,000	285,000	375,000
DWT Max	60,000	80,000	100,000	180,000	220,000	350,000	400,000

Table 2
Composition of the ports' ship fleets.

Ship Class	DWT	Port 1	Port 2
2 – Handymax	40,000	5%	0%
3 – Panamax	70,000	10%	3%
4 – Small Cape	100,000	0%	0%
5 – Cape	150,000	50%	97%
6 – Large Cape	180,000	25%	0%
7 – Very Large Cape	250,000	10%	0%

tion adopted one tank with a capacity of 5 million m^3 and a treatment rate of 500,000 m^3/h. We assumed a doubled capacity of the ship ballast pumps, so that it does not become a limiting factor during ship loading. This hypothesis was based on the fact that the ballast tank discharge process begins when the ships are berthed.

Thus, the simulation model should represent the normal operating condition of the ships in the ports, considering the loading rate, access restriction, maneuvering time and berth occupation. This process did not consider the restrictions external to berth operation. The main variables addressed in the validation were the transportation demand attended, berth occupation rate and average time spent in a queue. The total transportation demand was attended through the simulation. The occupation rates generated by the simulation model are close to the values obtained from the port operators. The total ballast water volume was discharged with no impact on port behavior. Thus, we considered the model to be capable of representing the onshore ballast water treatment system.

Table 3 presents the results of the simulation addressing the ballast water treatment system in the ports after model validation. The first simulation was designated Base-Alternative, as it refers to the current characteristics of the ports. The results follow these criteria: (a) attending the annual transportation demand and ballast water treatment at the lowest tankage possible; and (b) ensuring that the occupation rates and queues remain at the same levels as under validation conditions. In the beginning of the simulation, we assumed that the ballast water receiving tank was empty.

Fig. 3 presents a comparison of the Base-Alternative results with the data collected for 56 ships from Port 1 and 15 ships from Port 2. We verified that the results of the simulation model were within the range of the data collected for both ports.

The occupation of the ballast water storage tanks during ship operations is presented in Fig. 4. Over the one-year simulation, we obtained the used capacity of the tanks versus time. The results presented are the occupation averages for all of the model replications.

We observed that the tank occupation varied from 0% to 10% of the capacity between 40% and 60% of the time. This finding indicates that the capacity of the tanks is sufficient to store the whole volume of ballast water received without impacting the operation of the ships. The maximum occupation of the tanks was 70% approximately 2% of the time.

5.1. Sensitivity analysis

The ore carriers currently being manufactured are increasing in size. To analyze the effect of this increase, we tested 3 configurations considering the operation of VLOC Ships of 400,000 DWT in berth 2 of Port 1. Class 7 ships were generated to transport 5%, 10% and 15% of the total transportation demand. Portions of Classes 4 and 5 were substituted with ships of Classes 6 and 7. All of the other parameters were maintained according to the Base-Alternative simulation. The results are presented in Table 4.

Table 3
Results of the Base-Alternative simulation addressing the ballast water treatment system in the ports.

Description	Port 1	Port 2
Expected transportation demand (t)	90,000,000	25,000,000
Attended transportation demand (t)	89,978,000	24,989,000
Expected ballast volume (m^3)	27,000,000	7,500,000
Discharged ballast volume (m^3)	26,993,000	7,496,000
Average lay days per ship (days)	4,04	3,95
Berth occupation		
Berth 1 (%)	61%	70%
Berth 2 (%)	85%	0%
Berth 3 (%)	75%	0%
Ships attended by class		
Number of Handymax ships Class 1	54	0
Number of Panamax ships Class 2	116	11
Number of Small Cape ships Class 3	0	0
Number of Capesize ships Class 4	270	151
Number of Large Cape ships Class 5	112	0
Number of Very Large Cape ships Class 6	44	0
Number of VLOC ships Class 7	0	0
Ship queue		
Average number of ships in queue	4,31	0,95
Average time spent in queue (day)	2,64	2,13
Impact of onshore ballast water treatment on port operation		
Average time of cargo wait for unballasting (h/ship)	0,01	0,13
Tank capacity m^3	40,000	20,000

Fig. 5 shows the impact of including VLOC ships in the operational parameters of Port 1. The results remained similar to those of the collected data.

The impact of the VLOC ships on the behavior of the ballast water receiving tanks is presented in Fig. 6.

We observed that the tank occupation varies from 0% to 10% of the capacity 45% of the time. This indicates that the capacity of the tanks is sufficient to store the whole volume of ballast water received without impacting ship operations. The maximum occupation of the tanks was 70% approximately 2% of the time.

6. Discussion

The simulation results indicate that onshore ballast water treatment does not impact the loading capacity of the ships at the ports. All of the ships generated during the simulation were attended. The time of the interruption in loading caused by deballasting to an onshore station was less than 1 h per ship.

Ship unballasting occurs simultaneously with the ship loading. The unballasting time will always be less than the total time for ship loading because ships in ballast condition have only 30% of DWT. Analysis of the data gathered in 2005 showed that the average time of unballasting during loading is 17 h. Assuming that one Class 5 ship of 200,000 DWT had 60,000 m^3 of ballast water on

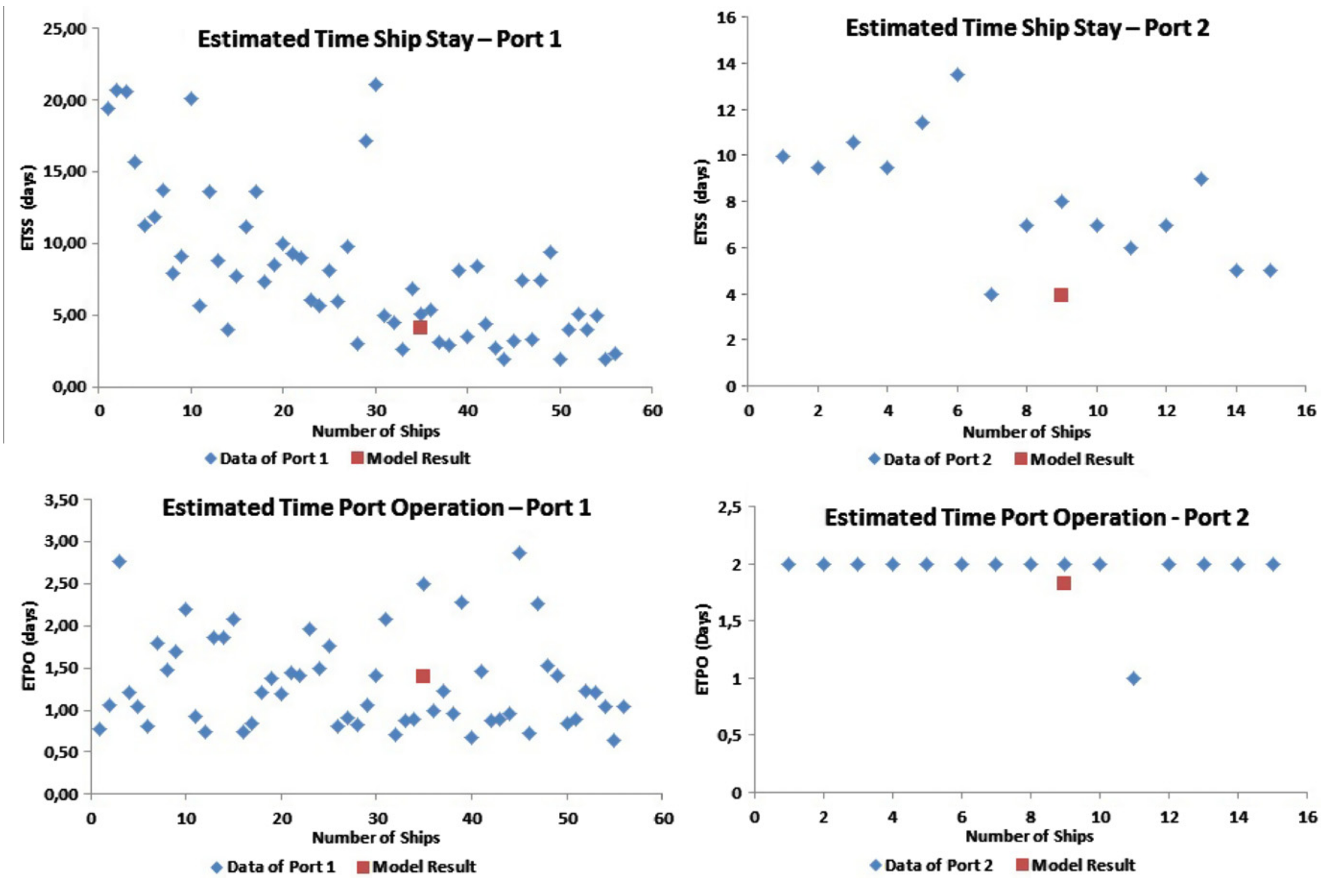

Fig. 3. Comparison of the ETSS and ETPO results between the Base-Alternative simulation and the collected data.

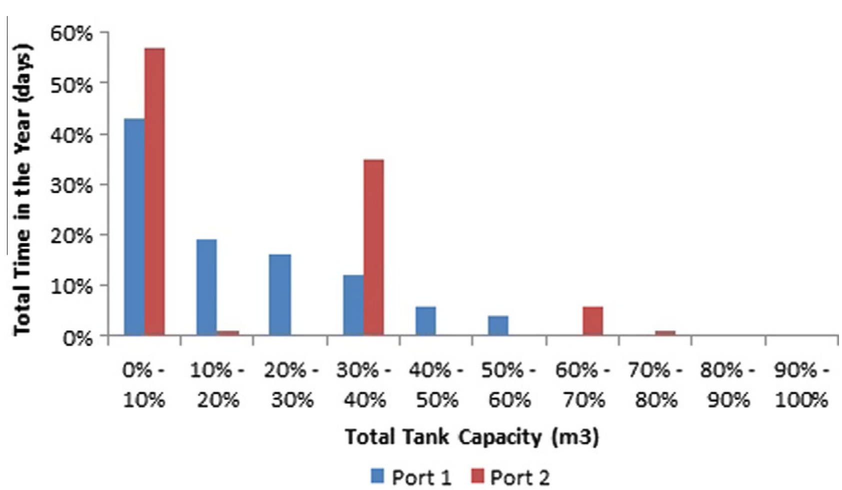

Fig. 4. Histogram of the tank occupation during the one-year simulation.

board, with a pumping capacity of 3000 m^3/h, the unballasting time would be 20 h. Assuming that this ship is loaded at a constant rate of 8000 tons per hour, the loading of the ship requires 25 h. However, for Class 1 and 2 ships, the unballasting rates are lower. For structural reasons, ship masters do not allow loading rates higher than 5000 tons per hour. Even under these conditions, the unballasting time tends to be inferior to the loading time.

However, if the receiving tank capacity is reduced and the ballast water treatment rate is not sufficient to treat the whole volume of ballast water collected, the port will be impacted by an onshore treatment system. If the ballast water treatment rate is higher than the average unballasting rate of ships, the filled capacity of the tank will tend to remain between 0% and 10%, as shown in Fig. 4.

The simulation model indicated that the port occupation rates presented values that are compatible with the rates practiced in ore iron ports in Brazil. As a function of the growth of exports, these ports aim at increasing their boarding capacities. The number of large ships discharging high amounts of ballast water in these ports annually has increased. This effect is reflected in the data pre-

Table 4
Results for VLOC ship deballasting at Port 1.

Description	Base	VLOC 5%	VLOC 10%	VLOC 15%
Expected transportation demand (t)	90,000,000	90,000,000	90,000,000	90,000,000
Attended transportation demand (t)	89,978,000	89,977,000	89,992,000	89,979,000
Expected ballast volume (m^3)	27,000,000	27,000,000	27,000,000	27,000,000
Discharged ballast volume (m^3)	26,993,000	26,993,000	26,997,000	26,994,000
Average lay days per ship (days)	4.04	3.93	3.87	4.15
Berth occupation				
Berth 1 (%)	61%	61%	61%	61%
Berth 2 (%)	85%	84%	76%	70%
Berth 3 (%)	75%	73%	82%	87%
Ships attended by class				
Number of Handymax ships Class 1	54	54	54	54
Number of Panamax ships Class 2	116	116	116	116
Number of Small Cape ships Class 3	0	0	0	0
Number of Capesize ships Class 4	270	270	242	214
Number of Large Cape ships Class 5	112	45	45	45
Number of Very Large Cape ships Class 6	44	79	79	79
Number of VLOC ships Class 7	0	12	24	36
Ship queue				
Average number of ships in queue	4.31	3.95	3.68	3.93
Average time spent in queue (day)	2.64	2.5	2.4	2.64
Impact of onshore BW treatment on port operation				
Av. time waiting for deballasting (h/ship)	0.01	0.02	0.02	0.09
Tank capacity m^3	40,000	40,000	40,000	40,000

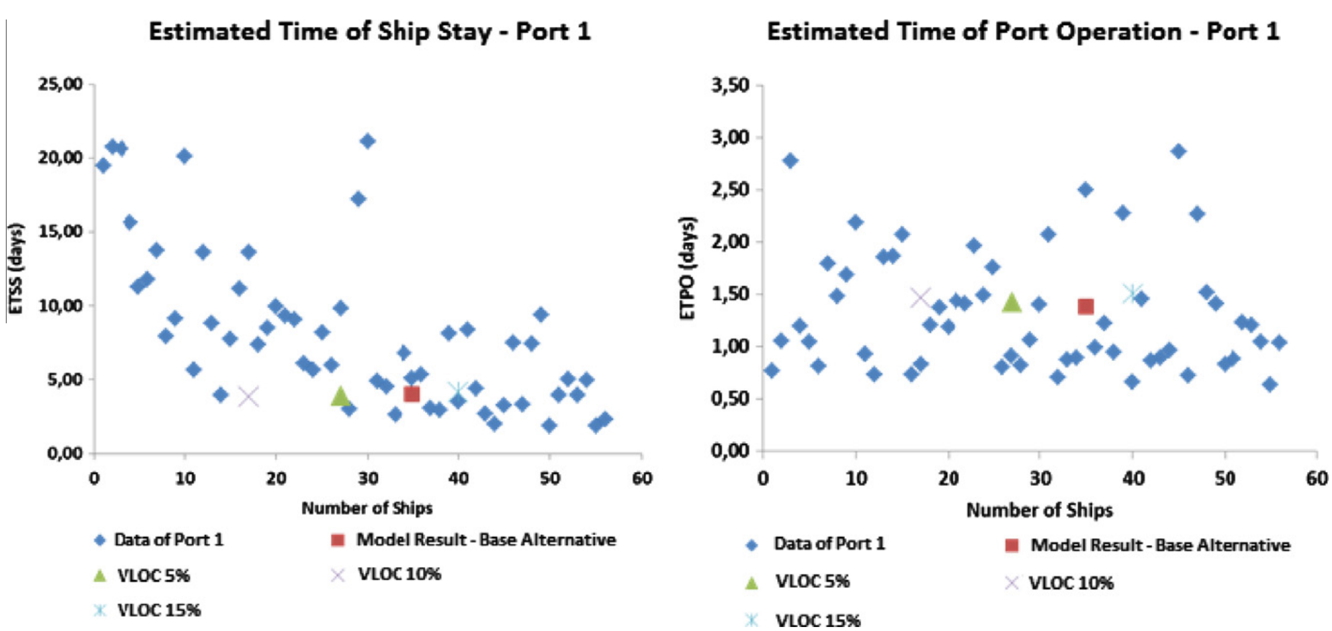

Fig. 5. Comparison between the simulated results and real data.

sented in Fig. 3. We observed that the ships remained waiting in queue for up to 20 days at Port 1 and up to 14 days at Port 2. Under the conditions observed at these ports, the cause of this ship waiting time is not related to ballast water treatment, but to other operational and commercial factors associated with the ports, the clients and the ship owners.

The operation of VLOC ships did not alter the treatment rates or tank numbers in comparison with the previous alternative (5000 m^3/h and tankage of 40,000 m^3). The number of lay days was similar to the validation condition, at approximately 4 days. The inclusion of VLOC ships did not alter the average occupation rate of the port because the total number of ships was reduced as the number of VLOC ships increased. However, because the volume of ballast water transported by each ship was greater, the tank occupation behavior was different from that in the Base-Alternative simulation. Thus, the statement that onshore ballast water treatment may increase the in-berth waiting time of ships will only be true if the tanks and treatment rates are not sufficient to receive and treat the whole volume discharged by the ships.

Moreover, we observed that with a static capacity of 40,000 m^3 and a treatment rate of 5000 m^3/h, it was possible to attend 596 ships per year in Port 1. With one 20,000 m^3 tank and a treatment rate of 2000 m^3/h, it was possible to attend 162 ships/year. This shows that the main characteristic of onshore treatment is its economy of scale, in contrast to onboard systems, which require one treatment system per ship (Cohen and Foster, 2000).

The capacity of the system proposed for the Port of Milwaukee is 3,000 gallons per minute (GPM), with a tankage capacity of

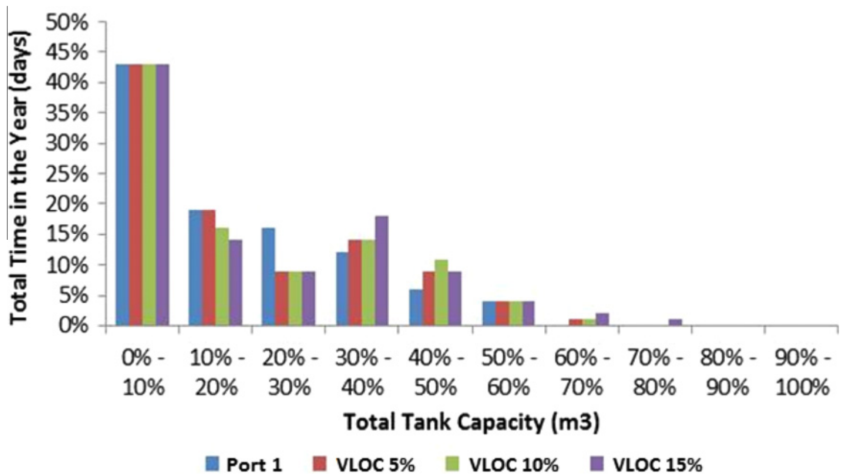

Fig. 6. Comparison of the port performances obtained via simulation and from real data.

0.5 million GPM (Brown and Caldwell, 2007). The sizing of the treatment and tankage system was performed through a deterministic calculation, considering the time necessary to empty the tank as a function of the capacity of the ballast tanks berthing in the port, which averages 0.13 MG. The main difference in our discrete event simulation model is the incorporation of randomness in the process, which assures greater reliability of the results.

However for the system to operate, it is necessary that ships carry out retrofitting (of Port Authorities, 2000). The costs to apply these modifications to ships can vary from $200,000 (Quarantine and AQISa, 1993; Brown and Caldwell, 2007) to $400,000 (Glosten, 2002). These adaptations are necessary so that all ships will be able to transfer ballast water to the onshore treatment station. These changes do not necessarily require modifications of the ballast water pumps, but only of the ships connections with the port.

7. Conclusions

Our conclusion regarding the viability of onshore treatment is based on the results of the simulation model. The results indicate that the level of service provided to the clients of the port in terms of occupation and queuing are not altered when the ballast water onshore treatment system is used compared to the current operation without the system. In a single port, it was possible to attend 596 ships per year, considering a single treatment system. Therefore, the onshore ballast water treatment system presents economy of scale. Furthermore, if the iron ore ports are provided with this type of treatment system, ships will not have to change their ballast water when they have no need of adjusting the air draft in the berthing access channel.

Moreover, the onshore treatment system can be adapted to reuse the treated ballast water, e.g., for industrial purposes. Potential restrictions on this type of treatment can be associated with the area available at a port. However, if there is in fact some kind of limitation, the tanks and the treatment system can be situated away from the port, as observed for desalination stations. In the context of reuse, once ballast water is collected, it can be sent to a desalination station to serve purposes of irrigation and human consumption.

Finally, as there are no ballast water treatment stations dedicated to the elimination of exotic species, the discrete event simulation model is a reliable tool for this type of evaluation. The TRANSBALLAST model can be applied to other ports with similar characteristics.

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