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Simulation modeling of the vessel traffic in Delaware River: Impact of deepening on port performance

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ABSTRACT

This paper deals with simulation modeling of the vessel traffic in Delaware River. The purpose is to study the impact of deepening on the navigational efficiency in the River. In this regard, vessel calls to terminals, lightering and barge operations, tidal and navigational rules in the River, terminal and anchorage properties as well as vessel profiles are considered in the model. The simulation model is specifically built to be able to perform scenario and policy analyses as well as a comprehensive risk analysis of the Delaware River and Bay area. This paper investigates effects of deepening on port performance measures. The statistics tracked in this respect are the overall port and terminal utilization, port times and terminal calls, anchorage visits and delays based on various vessel visits, categories and movements.

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1. Introduction

Delaware River has a history of more than 300 years as a commercial maritime route for handling import and export of raw and manufactured goods. Today it has more than 40 port facilities with their associated businesses located 60–100 miles up the River with about 3000 vessels visiting each year.

The region has proximity to the densest population base in the US and 27 million people living within 100 miles and 90 million within 500 miles give its ports a widespread natural consumer market. In this respect, approximately 65% of the region's cargo tonnage is in petroleum. Other major cargoes are steel, wood products, and perishable items such as fresh fruit, nuts, cocoa beans, and meat products. Major ports covered are Wilmington, Chester, Philadelphia, Camden, and Trenton, with major facilities at Delaware City, DE; Paulsboro, NJ; and Marcus Hook, PA [1–3].

The River is the port of call for large commercial ships and tug/barge units that can only navigate in the main ship channel. The River's 40-foot channel appears to be shallow when compared to other ports in the region, restricting its ability to compete for shipments via the new generation of mega-ships that require deeper drafts.

In view of the current expansion of the Panama Canal, deepening of the main ship channel of Delaware River to 45 ft has been proposed and debated over a number of years. The project consists of the navigation channel from deep water in Delaware Bay to Philadelphia Harbor, PA and to Beckett Street Terminal, Camden, NJ. The plan introduces modifying the existing Delaware River Federal Navigation Channel from 40 to 45 ft below Mean Low Water (MLW) and provision of a two-space anchorage to a depth of 45 ft at Marcus Hook. Accordingly, the benefits are expected to be the reduced costs of transportation realized through operational efficiencies (reduced lightering and light-loading), and the use of larger

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and more efficient vessels, both resulting from navigation improvements by means of cost reduction per ton for shipping commodities into or out of the Delaware River Port System [4,5].

In this respect, the motivation behind this study is to analyze the impact of deepening on navigational efficiency based on port performance measures. Navigational benefits may include shortened port time per vessel call, lesser anchorage delays and lesser tidal delays, among others. When a port is deepened, it becomes a new port and therefore, it is essential to develop a model of the current scenario to provide a practical and realistic tool for performance analysis. This helps to investigate the dynamics of vessel movements once the River is deepened, possible increases in vessel calls, possible changes in vessel particulars, and changes in navigational rules. The proposed model is also aimed to be used to examine feasibility and the effects of port expansion projects and to perform logistics and risk analysis in the Delaware River and Bay (DRB) area (Fig. 1). These may include construction of new terminals, installation of new infrastructure facilities or energy projects such as off-shore wind farms. Clearly, such a tool can be developed for other ports and waterways for the same objectives.

2. Literature review

Simulation modeling has been used in various fields where analytical models cannot be used due to complex nature of problems. Simulation studies in maritime transportation domain can be categorized under applications on port/terminal operations and logistics, modeling of vessel traffic on waterways for scenario and policy analyses and using simulation platforms as a tool to evaluate accident probabilities, risks and various economic and technical issues.

There are numerous studies in literature in which simulation techniques were used to study terminal logistics which is beyond the scope of this study. Some of these use simulation models for solving optimization problems. Among them, Lag-

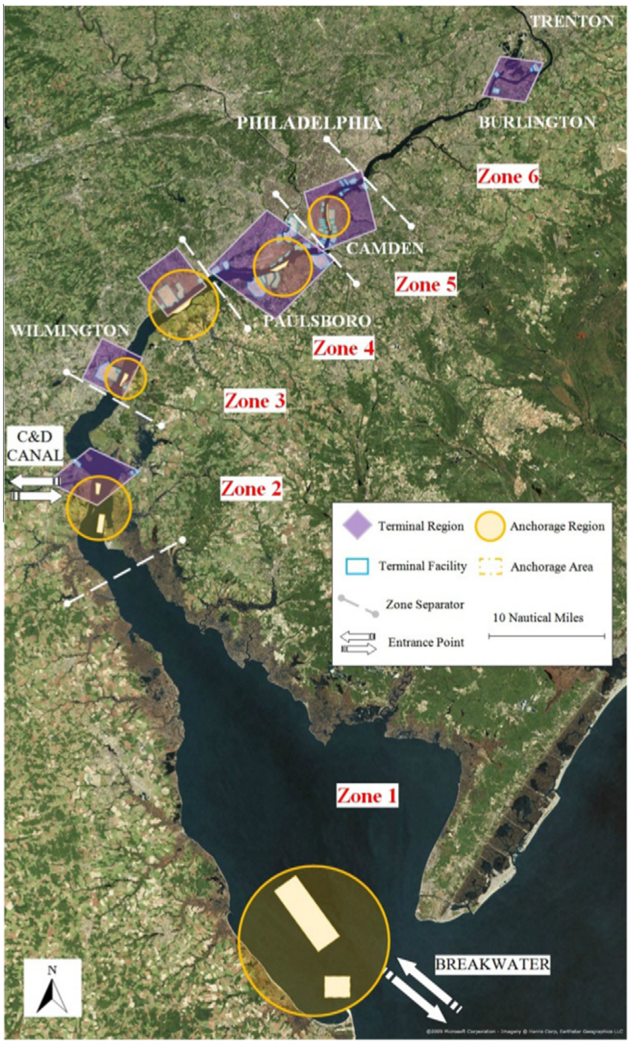


Fig. 1. Delaware River and Bay.

ana et al. [10] focused on parallel processing of simulation optimization for allocation of berth segments and cranes to shipping services based on a simulation model of a queuing network. Similarly, Legato et al. [11] worked on optimization of crane transfers in a container terminal using a statistical ranking and selection technique to simulation output to select the best system design. Arango et al. [12] studied berth allocation problems at Port of Seville integrating a genetic algorithm into an Arena simulation model for optimization. An extensive classification and literature review on container terminal operations can be found in [13].

On the other hand, literature on simulation modeling of vessel traffic on waterways is not large but growing. Golkar et al. [14] developed a simulation model for the Panama Canal as a tool for scenario and policy analyses. Thiers and Janssens [15] developed a detailed maritime traffic simulation model for the port of Antwerp, Belgium including navigation rules, tides and lock operations in order to investigate effects of a container quay to be built outside the port on the vessel traffic and especially on the waiting time of the vessels. Merrick et al. [16] performed traffic density analysis which would lead later to the risk analysis for the ferry service expansion in San Francisco Bay area. They tried to estimate the frequency of vessel interactions using a simulation model they developed, in which vessel movements, visibility conditions and geographical features were included. Cortes et al. [17] simulated both the freight traffic and terminal logistics for Port of Seville, Spain using Arena software focusing on port utilization (and dredging is recommended to accommodate bigger vessels for potential growth). Smith et al. [18] worked on congestion in Upper Mississippi River through building a traffic simulation model and tested different operating conditions. For the Strait of Istanbul there is considerable literature bringing different perspectives in which simulation modeling was used for scenario and policy analyses. Köse et al. [19] developed an elementary model of the Strait of Istanbul and tested the effect of arrival intensity on waiting times. Ozbas and Or [20] and Almaz et al. [21] developed extensive simulation models including vessel types, cargo characteristics, pilot and tugboat services, traffic rules, and environmental conditions and investigated effects of numerous factors on different performance measures such as transit times, waiting times, vessel density in the Strait and service utilizations.

In addition to these, in various studies vessel traffic simulation was inherently used as an environment for further analysis of accident probabilities, risks and various economic and technical issues. Ince and Topuz [22] used traffic simulation environment as a test bed for development of navigational rules and to estimate potential system improvements in the Strait of Istanbul. Traffic simulations including traffic rules, weather and relevant environmental conditions were also developed by van Dorp et al. [23] for Washington State Ferries in Puget Sound area and Merrick et al. [24] for the Prince William Sound in order to perform risk assessment through integrating accident probability models. In similar studies Uluscu et al. [25] used a traffic simulator to test and deploy a scheduling algorithm for transit vessels in the Strait of Istanbul and Uluscu et al. [26] developed a dynamic risk analysis map based on an extensive vessel traffic simulation for the Strait of Istanbul. Goerlandt and Kujala [27] also used vessel traffic simulation to evaluate ship collision probability in the open sea where environmental conditions are negligible. Somanathan et al. [28] investigated economic viability of Northwest Passage compared to Panama Canal using simulation for vessel movements and environmental conditions. Martagan et al. [29] built a simulation model to evaluate the performance of re-routing strategies of vessels in the U.S. ports under crisis conditions. Quy et al. [30] used traffic simulation which includes tide and wave conditions in order to find optimal channel depths for vessel navigation by minimizing the grounding risk based on a wave-induced ship motion model.

There are also studies which are relevant and can guide analyses of several components in the development of a traffic simulation model. Asperen et al. [31] investigated different vessel arrival methods which can be used in simulation studies and compares their effects on port efficiency. Jagerman and Altiok [32] studied modeling of negatively correlated vessel arrivals and developed approximations for the queuing behavior. Pachakis and Kiremidjian [33] proposed a ship traffic modeling methodology for ports in which functional relationships are used among ship length, draft and cargo capacity.

Maritime transportation studies on Delaware River and Bay are limited in number. However, the work of Andrews et al. [34] is closely related to the scope and some components of our study. In this work the authors used simulation for modeling of oil lightering in Delaware Bay and investigated effects of alternative policies on service levels. Lightering operations were modeled in detail and calibrated to match historical data statistics. Number of lightering barges, their capacities, loading and discharge rates, heating features, weather sensitivities and priorities that are used in the assignment procedure and tidal issues were all taken into account. Moreover, a representative scheduling algorithm for lightering barge assignments were tried to be built. As a contrast to the work of Andrews et al., our study has further simplifying assumptions to model the lightering operations such as neglecting heating features, weather sensitivities and priorities. However, the general modeling perspective, scheduling algorithm, service times being dependent on the volume of oil to be lightered and the barge in use and possibility of two barges working a vessel at the same time are all analogous to our study.

Investigation of impacts of deepening on various port performance measures is scarce in literature. Grigalunas et al. [35] have analyzed benefits and costs of deepening in Delaware River from an economic perspective. In their study, they described the benefits of deepening for the state of Delaware based on share of the hinterland area population for transportation savings and direct nonmarket benefits. They also recognized unquantifiable as well as qualitative effects, and hence tried to justify the proposed deepening project for the cosponsor's side.

This paper presents a simulation model focusing on the maritime activities in the current as well as deepened scenarios in the Delaware River and Bay area. The main contribution of the paper is to emphasize the need for such analysis during deepening/dredging planning processes in any port or waterway system. To the best of our knowledge no such directly related work to deepening/dredging was located in literature.

3. Port operations in Delaware River and Bay

Delaware River is both geographically and operationally one of the most significant waterways in the East Coast. Port operations and maritime activity in the River extends from Breakwater entrance all the way to Trenton, NJ. There are two entrance points to the Delaware River port system. Around 93% of vessel arrivals are through Breakwater (BW) and the rest is through Chesapeake and Delaware Canal (CD). Vessel profiles are in line with the cargo types being carried to terminals and are mostly tankers (30%), cargo containers (15%), bulk vessels (14%), refrigerated vessels (11%), vehicle vessels (10%) and general cargo vessels (8%). Aside of the regular cargo vessel traffic there is also tug/barge traffic carrying cargo in and out of the port.

There are rules and regulations governing the vessel traffic in the River such as the maximum fresh water draft for river transit from BW to Delair, NJ is 40 ft and from Delair to Trenton, NJ it is 38 ft. For vessels using CD the maximum draft limitation is 33 ft.

Along with the rules and regulations, oceanic tidal activity significantly influences the entrance of large vessels from BW. Tides recurring in almost 12-h periods are causing changes in the water level up to 6 ft above mean lower low water (MLLW) and restrict the sailing of the deep draft vessels through the River. Thus, especially inbound vessels with more than 35 ft draft are affected by tide and experience extra delays in port operations.

Lightering is another significant activity in the system. The maximum salt-water draft in the entrance of Delaware Bay is 55 ft and Delaware River's main channel allows travel of vessels below 40 ft fresh water draft. Based on this regulation, deep draft vessels carrying cargo that could be transferred to lightering barges (mostly tankers carrying petroleum products) can do lightering depending on the water depth at the first terminal they will be visiting. In general, there are four lightering barges serving vessels to be lightered and going up and down in the River to terminals and to Big Stone Beach Anchorage (BSB) which is the designated lightering area.

Clearly, there is a destination terminal and possibly more than one destination for every vessel arriving at the River. Therefore there needs to be an itinerary planning for the vessels' navigation in the River. There is a variety of terminals each having its own capacities (number of berths) and operational details. Major terminals in the system are petroleum and chemical refineries, container cargo facilities, dry bulk and break bulk handling terminals, and refrigerated cargo facilities.

Also there are several anchorage areas throughout the River for vessels to wait between terminal visits due to berth unavailability, tidal activity, maintenance or emergency reasons.

4. Simulation model

The main goal behind the model development is to constitute an accurate platform to study key issues, such as deepening, regarding the Delaware River's operation via scenario analysis such as increase in vessel arrivals, deepening the River and changes in the operational/navigational policies. A detailed model is needed to answer questions regarding these key issues. Considering the number of terminals, berth capacities and types of cargo vessels among others, simulation methodology appears to be the right approach to study various aspects of the geography of interest. Therefore, a high-fidelity simulation model of the vessel traffic in DRB is developed involving all vessel types and all of the port terminal facilities along the River from entrance to Trenton (Fig. 2). Arena 11.0 simulation software is used in the development of the model [9].

The simulation model involves all cargo vessel types, their particulars, arrival patterns, their trips in the River, and incorporates all the navigational rules as explained in the Coast Pilot [2]. Tidal activity, lightering operation and anchorage holding activity along with terminal operations to the extent of vessel berth holding (excluding internal terminal logistics) are also included in the model.

Detailed historical data are obtained from the Maritime Exchange for the Delaware River and Bay [1] on vessel arrivals and vessel movements for the years between 2004 and 2008. The input data include arrival times, vessel characteristics of length, beam, underway draft, max draft and gross tonnage, travel times, terminal holding times, and terminal transition probabilities that are the probabilities of going from one terminal to another. As usual, data for random components were analyzed and distributions fitted. In addition to these, tidal activity is generated by reading historical data obtained from the National Oceanic and Atmospheric Administration (NOAA) through text files into the model.

The objectives of this paper center around the investigation of the impacts of some key issues regarding dredging and deepening of DRB on port performance. These are:

– Increase in vessel arrivals due to trade growth.
– Deepening the River and dredging some terminals by 5 ft.
– Change vessel configuration and bring larger vessels.

Relevant scenarios are described in the scenario analysis section below.

5. Model structure

The simulation model is developed paying attention to technical issues regarding the random events occurring in the River. In line with the objectives of the study, the simulation model is developed with the major components listed below that are necessary for a realistic representation of the current traffic system in Delaware River and Bay.

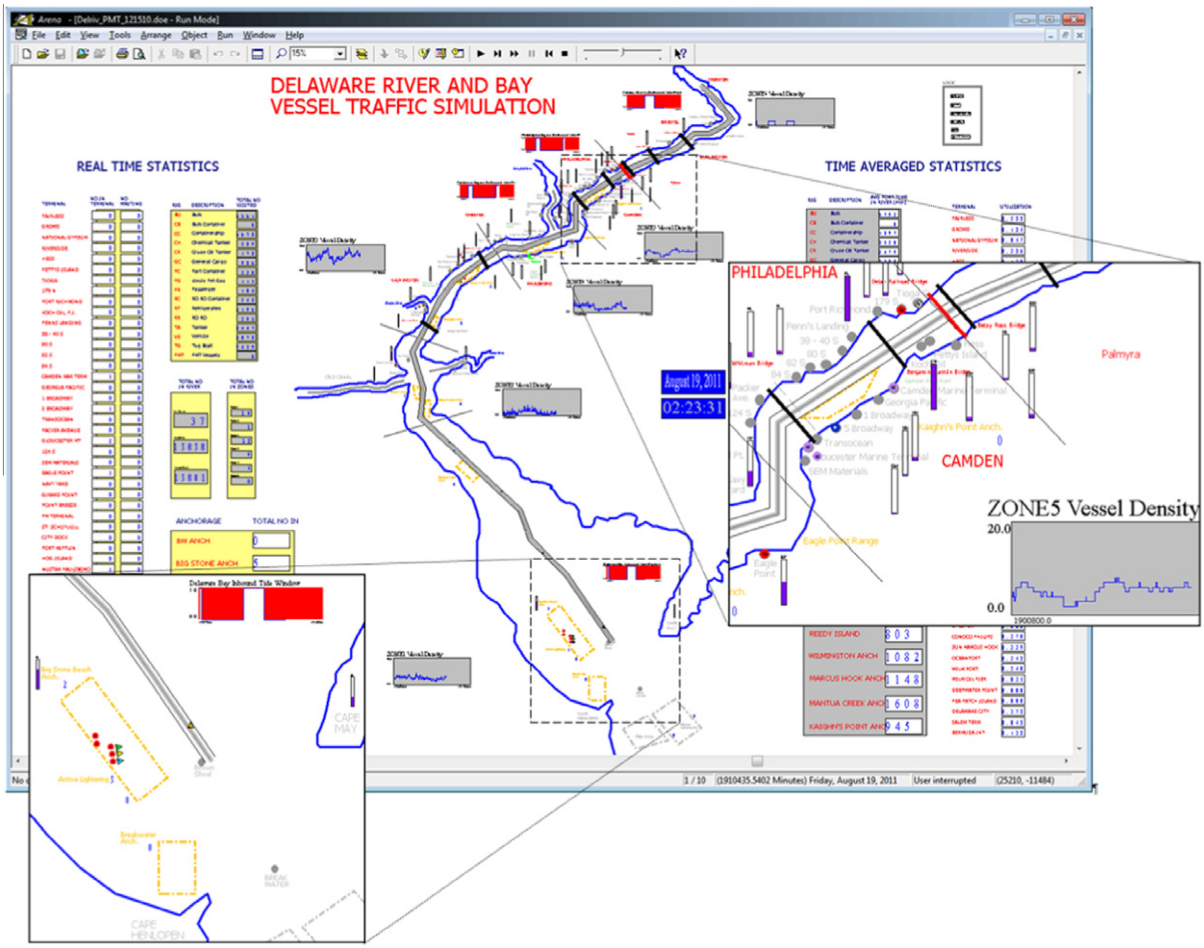


Fig. 2. A high level view of the Arena simulation model with specific zooms at Big Stone Beach Anchorage and Philadelphia region.

– Randomized vessel arrivals at BW and CD.
– Randomized vessel characteristics of length, beam, underway draft, max draft and gross tonnage.
– Terminal calls based on a randomized itinerary generation.
– Vessel navigation with randomized vessel travel times to terminals and anchorages.
– Tidal and navigational rules in the River.
– Lightering rules and procedure.
– Terminal berth reservation procedures.
– Anchorage selection procedure.
– Randomized vessel holding times at terminals.

Fig. 3 illustrates the structure of the simulation model with the aforementioned components. The figure comprised of three segments. The top and the bottom segments show the procedure flows whereas the middle segment depicts the processes and delays in the port. The solid arrows are for procedure flows which do not include time delays. The dashed arrows represent movements of vessels in the River where travel times are involved.

Note that weather conditions such as wind, visibility and rain are not considered in the model due to their marginal impact on the operations for the scope of this work. Below the model components mentioned above are described in some detail.

5.1. Vessel generation

Vessel types considered in this study are selected through their majority in the historical data provided by the Maritime Exchange for the Delaware River and Bay [1] that has been using vessel categories based on vessel characteristics and cargo being carried. This categorization is adopted in this study with few vessel categories combined in order to minimize loss of information and enhance simplicity. In this respect, major vessel types visiting Delaware River and Bay area can be classified

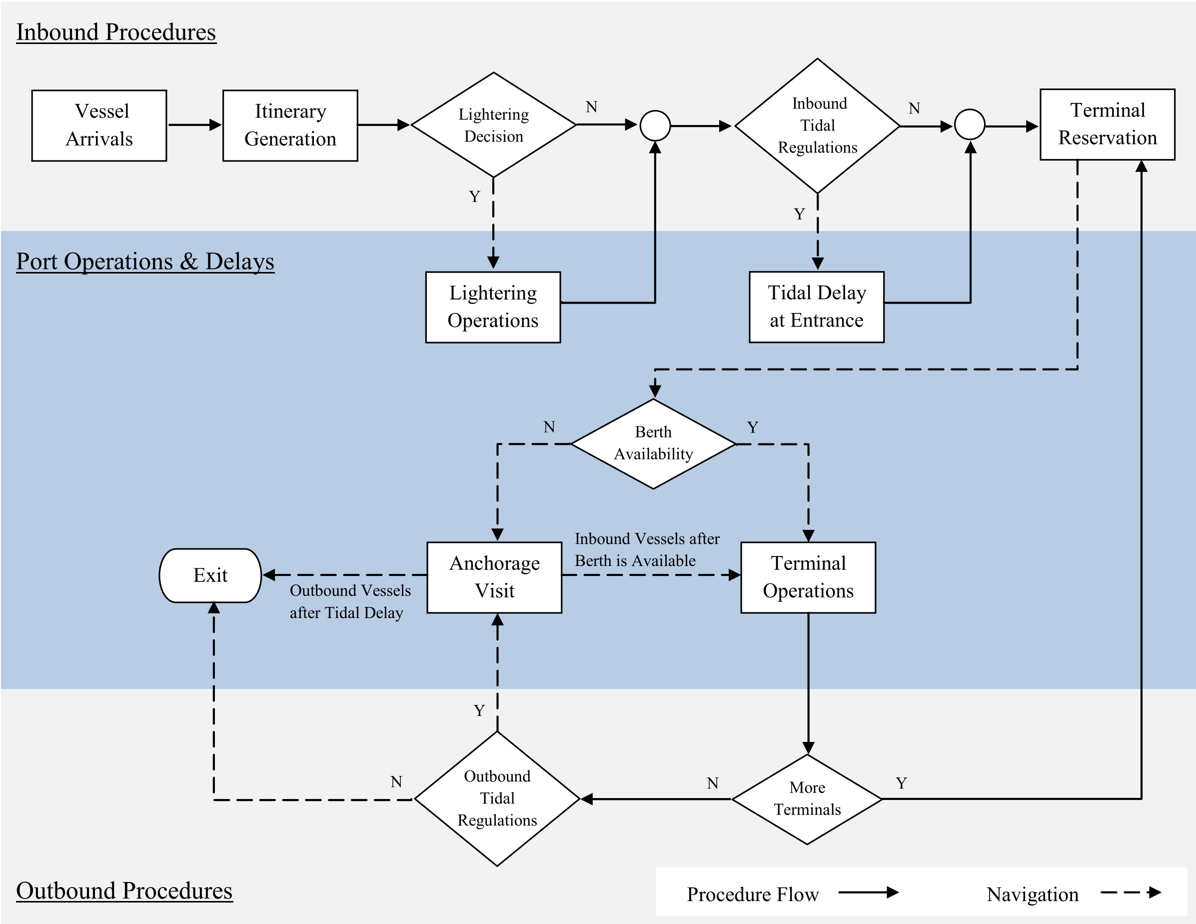


Fig. 3. Model structure and vessel based flow processes.

into 14 categories. These vessel types are Bulk (BU), Containership (CC), Chemical (CH), Non-flammable Product (NP), General Cargo (GC), Part Container (PC), Liquid Petroleum Gas (PG), Passenger (PR), RO-RO Container (RC), Refrigerated (RF), RO-RO (RR), Tanker (TA), Vehicle (VE) and Tug Boat (TG).

Each vessel type may have entries from BW and/or CD. Based on the interarrival time analysis performed for each vessel type, probability distributions are fitted and modeled for each stream. Note that we have also taken seasonality into consideration for PR vessels (that vessel generation is active only in spring-summer season) while it is neglected for other vessel types. Vessel particulars of length, beam, underway draft, maximum draft and gross tonnage have all been assigned based on statistical analysis of the historical data.

Arrival processes are analyzed for each vessel type at BW and CD independently. Interarrival times are stochastic hence, resulting random total number of vessels. As an example, the histogram and interarrival time distribution results of the BU vessels at BW obtained from Arena's Input Analyzer [9] are presented in Table 1. In this table, interarrival times (in minutes) of 1848 bulk vessels entered from BW in 5 years in the historical data are fitted to a gamma distribution with scale parameter (β) 1560 and shape parameter (α) 0.909. Note that, fitting distribution to data is performed using Arena's Input Analyzer and the best-fit probabilistic distribution is selected considering shape of the histograms and graphical observations, square errors achieved, goodness-of-fit tests as well as characteristics of the process.

In addition, correlations among interarrival times up to ten lags are also inspected and resulting correlogram is depicted in Fig. 4 for the BU vessels. In most of cases, correlations are not significant. In a few cases they range between −0.18 and 0.38 at lag 1. However, their annual numbers of calls are not significant and therefore they are neglected to preserve simplicity in the model. Thus, the vessel arrivals are assumed to be independent of each other and generated by probabilistic distributions while the PR vessels are only generated in spring and summer seasons.

For a realistic characterization of vessels and cargo loading profiles of different terminals underway drafts of vessels are analyzed and modeled using empirical distributions for each terminal, vessel type and entrance point triplet, independently. Thus, based on the first terminal to be visited, an underway draft is assigned to each vessel generated in the model.

Table 1
Typical Input Analyzer distribution fit summary for interarrival times (minutes) of the BU vessels at BW.

Distribution Summary

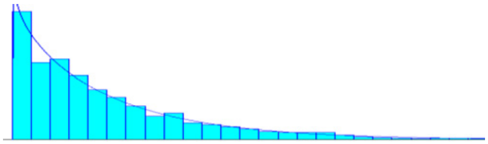
Distribution	Gamma
Expression	GAMM(1560, 0.909)
Square Error	0.00094

Chi Square Test

Number of intervals	23
Degrees of freedom	20
Test Statistic	27.2
Corresponding p-value	0.14

Kolmogorov-Smirnov Test

Test Statistic	0.0273
Corresponding p-value	0.126



Data Summary

Number of Data Points	1848
Min Data Value	0
Max Data Value	11100
Sample Mean	1420
Sample Std Dev	1470

Histogram Summary

Histogram Range	0 to 11,100
Number of Intervals	40

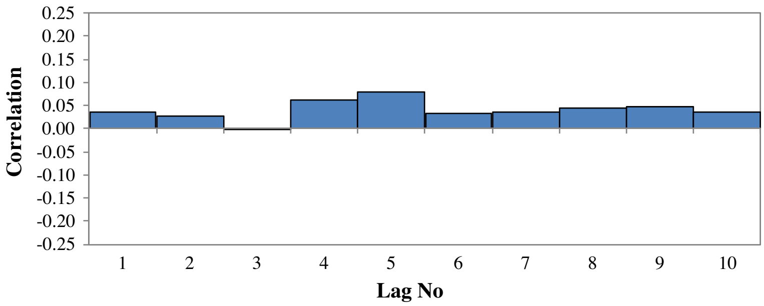


Fig. 4. The correlogram of interarrival times of the BU vessels at BW.

Since vessels are not fully loaded when visiting terminals their underway drafts are expected to be less than their maximum drafts. Based on this relation, a regression model is produced with the data on hand for each vessel type. Thus, using the underway draft produced in the model, the maximum draft of a vessel can be estimated.

Vessel particulars of maximum draft, length, beam and gross tonnage are expected to be closely related to each other since they are defining the size of the vessel. Therefore, once any of these size-related elements is known, other vessel particulars can be estimated. First, maximum draft is estimated using the underway draft. Then, regression models are built based on the data on hand in a similar manner to [33] to estimate other vessel particulars being dependent on maximum draft. Fig. 5 is depicting regression models built for CC vessels and is given as an example to describe how vessel particulars are generated in the model. Each vessel type has its own regression models given as such. These regression models are based on the data on hand and regression types (equations) are selected by their best match comparing adjusted *R*-squared values. In some cases given in Fig. 5, selecting non-linear relationship improves the adjusted R-squared values and graphically gives better fit.

5.2. Itinerary generation

The basic purpose of a vessel visiting DRB is loading and/or unloading cargo in a terminal residing in the DRB port system. Vessels coming to DRB may visit more than one terminal and thus itinerary generation is needed for arriving vessels to determine the sequence of ports they visit.

In the data analysis phase, for each vessel type investigated, an itinerary generation matrix is produced. This matrix is comprised of probabilities of vessels departing from one terminal and ending up in another. As shown in Table 2, each row in this matrix represents all possible transitions from a terminal to other terminals, and thus adds up to 1.

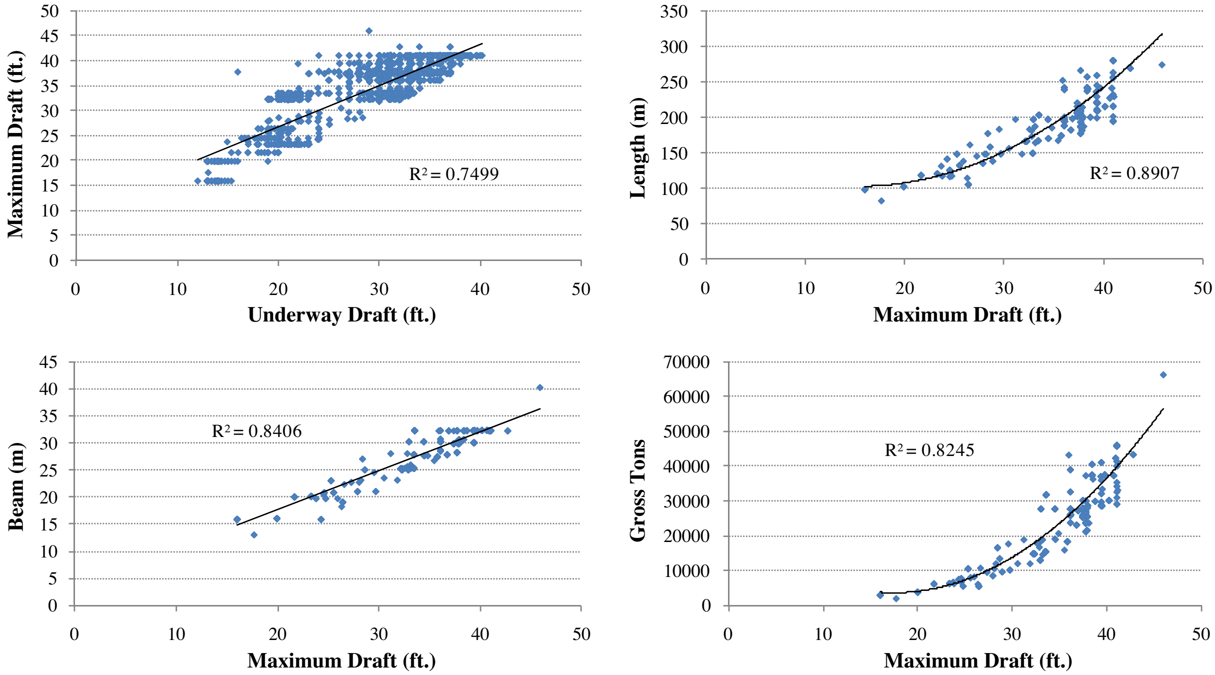


Fig. 5. Typical regression models for vessel particulars of maximum draft, length, beam and gross tonnage for the CC vessels.

Table 2
Itinerary matrix for PG vessels.

Starting terminals	Destination terminals				
	BW	Girard Point	Hess	Sun Marcus Hook	Wilm oil pier
BW	0	0.240	0.007	0.753	0
Girard Point	0.861	0	0	0.139	0
Hess	1	0	0	0	0
Sun Marcus Hook	0.683	0.308	0	0	0.008
Wilm oil pier	1	0	0	0	0

Once a vessel is generated and its particulars are assigned in the model, an itinerary is produced based on the vessel's type. This itinerary is stored in an array and it forms the backbone of the vessel's visit and its movements in the River.

5.3. Navigation in the River

Based on geographical importance, terminal and anchorage locations, and considering rules and regulations to facilitate decisions to be made during movement of vessels, the River is separated into six zones in the model whose entrance and exit points are defined by virtual reference stations (Fig. 1). Thus, each terminal and anchorage location is defined by their zone number in order to facilitate handling of navigational rules and vessel movements. A numbering scheme is also established covering terminals, anchorages and virtual reference stations in order to navigate a vessel from one point to another. Reference stations constitute the keystones of navigation in the River in the model. Before a vessel starts from a station, a target station is determined in the reservation procedure that is to be described in Section 5.6. This target can be either an anchorage or a terminal based on berth availability and navigational rules. If the target station is in the same zone, vessel is sent directly to the target station. Otherwise, it is sent to the closest reference point to its current location and from there vessel is sent to the next reference station in the same direction until it reaches to the entrance of the zone in which the target station resides. The same procedure is used each time a vessel needs to move in the River.

Distance and travel time matrices are important components of the navigation logic in the model. Distance matrix includes distances for all possible inter-station travel supported by the data. Travel time matrix, similar to the itinerary matrix, includes a probability distribution representing travel time from a terminal to other possible terminals. Thus, travel times of the vessels are calculated based on predefined probability distributions specific to vessel types, source terminal and destination terminal combinations. As an example, a direct trip of a BU vessel from BW entrance to Camden/Beckett Street terminal is modeled using $(328 + 323 * \text{BETA}(4.28, 4.36))$ distribution using historical data, as obtained from Arena's Input

Analyzer. Before a trip starts, a travel time is generated and the vessel's speed is determined based on the distance from the source to the destination. Until the trip ends, the vessel uses the calculated speed to move from one station to another in the model. It is assumed that the tide does not have impact on vessel travel times. The oceanic tide activity in the River affects the entrance and movements of large vessels in the system. However, speed of tide/current has minimal effect on vessel speeds, therefore ignored in the model.

5.4. Regulations

Navigation in the River is controlled by a number of regulations that are clearly explained in the Coast Pilot [2], some of which are given below:

a. *Lower River Tide Rules*
   1. All vessels arriving with fresh water (FW)[1] draft in excess of 37 ft or over Panamax[2] size beam (106 ft) having a fresh water draft in excess of 35'–06" shall only transit during flood current.[3]
   2. Vessels outbound from Paulsboro, NJ and above, having a fresh water draft of 37 ft and up to 40 ft should arrange to sail 2 hours after low water.

b. *Upper Delaware River Rules*
   1. Vessels inbound 32′–06″ FW or greater up to 35′–00″ FW in draft should arrive in Philadelphia harbor no later than 9 h and 15 min, or earlier than 5 h and 45 min from slack flood current at Cape Henlopen.
   2. Vessels inbound 35′–01″ FW or greater up to 38′–06″ FW in draft should arrive in Philadelphia harbor no later than 8 h and 15 min, or earlier than 5 h and 45 min from slack flood current at Cape Henlopen.
   3. Vessels outbound 32′–06″ FW or greater up to 38′–06″ FW in draft, should sail from terminals above the Delair Railroad Bridge between 1 h before high water and 3 h after high water at the dock at which it is sailing.

Note that there are a number of other rules included in the model for a realistic representation of navigation in the River.

5.5. Lightering operations

Lightering operations in Delaware River basically concern tankers. This is due to the fact that the majority of the vessels traveling through the River are tankers and about 75% of the tankers entering from BW have a maximum draft above 40 ft. In particular, 43% of the tankers have underway draft above 40 ft and need lightering. All these tankers carrying oil are generated from their specific arrival process in the model.

In order to utilize their capacity, tankers traveling from the open sea may arrive at the entrance with a higher underway draft and cannot enter the River. Following their arrivals, vessels in this category check the maximum berth depth in their destination terminal and if their underway draft exceeds the berth depth, they are directed to the BSB to do lightering. There, they transfer some of their cargo to lightering barges to reduce their draft down to 40 ft so that they can proceed into the River. This operation is significant in DRB and it is analyzed and modeled with emphasis for the purpose of establishing a basis for scenario analyses.

In addition to characterization of the 14 vessel types, four lightering barges (LB) which have been active during the time span in the historical data are also generated and maintained in the model. These barges are specified by their original size and approximate loading and discharging capacities as also discussed in [34].

Lightering procedure is modeled as follows. Once tankers enter from the BW entrance, those having higher drafts above their first terminal limits are required to do lightering before sailing into the main channel. Tankers to be lightered go to BSB and call for an available lightering barge. Depending on lightering demand of the tanker, more than one lightering barge may serve the vessel. Once a lightering barge arrives, lightering starts and continues depending on loading speed of the barge and some random preparation time. After lightering ends, tankers may spend some extra time in the anchorage area or may directly set out for their first destination terminal.

Lightering barges are also assigned a specific itinerary based on their individual itinerary matrix. Their holding times per terminal are determined depending on the number of terminals they visit in each trip based on particular lightering barge's cargo discharge rate and the amount of cargo it is carrying. As an example, if an LB is carrying 256,000 barrels of oil to terminals given the discharge speed is 32,000 barrels per hour and two terminals to be visited, holding time is evenly divided between terminals and would be around 4 hours for each terminal. LB transit times are calculated based on the distance to be traveled and a fixed average speed of 10.8 knots for all LBs (as suggested by lightering company, OSG Inc.).

Lightering demands of tankers are calculated using a regression model (Fig. 6). According to data on hand, lightering demands of tankers are found to be highly correlated with their gross tonnage and the amount of draft to be lifted for the tanker to safely visit its first destination terminal in the River. The lightering regression equation used in the model in which the adjusted *R*-square is found to be 0.9627 is given below:

[1] The salinity and water temperature affect water density, and hence how deeply a ship will hold in the water.
[2] Panamax size is the maximum dimensions allowed for a ship transiting through the Panama Canal (Length: 294.1 meters, Beam: 106 ft, Draft: 39.5 ft)
[3] Flood current is the tidal current associated with the increase in tide height.

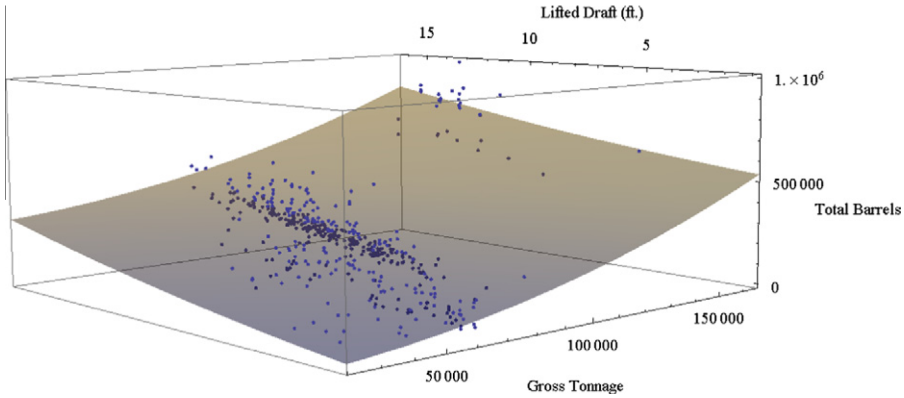


Fig. 6. Lightering regression plot.

$$L = 1.63163 \times 10^{-5} \times GT^2 + 0.4544 \times GT + 421.771 \times D^2 + 11551.983 \times D \quad (1)$$

where L is the lightering demand in barrels, GT is the gross tonnage and D is the draft to be lifted in ft in the lightering operation. The intercept in the equation is assumed to be zero in order to prevent negative values for the lightering demand.

5.6. Terminal reservation mechanism

A reservation system is created to manage vessel-terminal berth pairings. Vessels generated in the system are supposed to have reservations in these target terminals before starting their trip for that terminal. Reservations are necessary in order to plan anchorage usage in case there is no available berth at the target terminal. Hence, using the reservation system, efficient and orderly movement of vessels in the River is achieved.

A reservation for a terminal is the selection of a suitable berth considering draft/cargo limitations and berth availability. Each and every berth in the River has an availability record in the system. Besides, if terminals have size limitations among their berths or have specific cargo handling assignment, these details are also incorporated in the model. Thus, a reservation is made by updating the availability record for the next vessel arrival for a particular berth.

Reservations for the first terminal visits of the vessels are performed at the entrances (BW and CD) of the River. Succeeding terminal reservations are performed at terminals when vessels are ready to depart. For vessels using Breakwater Anchorage (BWA) or BSB right after entering the system, reservations are performed when they are ready to leave the anchorage.

5.7. Anchorages

There are 7 major anchorage areas in DRB considered in the model. BWA and BSB at the BW entrance; Reedy Point Anchorage (RP) at the CD entrance; and Wilmington Anchorage (WA), Marcus Hook Anchorage (MHA), Mantua Creek Anchorage (MCA) and Kaighn's Point Anchorage (KPA) in the River are included in the model.

Anchorages are used for several purposes and each anchorage has its own particulars and capacity in the system. BWA is mostly used for waiting due to tide or other several needs while entering the River. BSB is only used for lightering purposes and possible other needs after the lightering process. All other anchorages are used prior to a terminal visit. MHA is also used for waiting due to tide for outbound vessels. The two anchorages at the BW entrance do not have capacity issues while all other anchorages have length, draft and capacity limitations (Table 3).

Anchorage visits are basically not random but they are planned based on decisions due to terminal berth availabilities, decisions due to rules and regulations and minor random visits for maintenance and other possible reasons.

Table 3
Anchorage draft, length and vessel capacity limitations [2].

Anchorage	Draft	Length	Capacity
Kaighn's Point	⩽30 ft	⩽600 ft	7
Mantua Creek	⩽37 ft	⩽700 ft	6
Marcus Hook	⩽40 ft	–	6
Wilmington	⩽35 ft	⩽700 ft	3
Reedy Point	⩽33 ft	⩽750 ft	5
Big Stone Beach	⩽55 ft	–	–
Breakwater	⩽55 ft	–	–

Table 4
Typical holding time distributions used for BU and TA vessels.

Vessel type	Terminal	Holding time distribution (min)
Bulk (BU)	Camden/Beckett Street	115 + WEIB(5500, 1.54)
	Packer Avenue	567 + 1.31e+004 ∗ BETA(1.77, 3.66)
	Wilmington port	547 + WETB(3110, 1.37)
	5 Broad way	UNIF(920, 2552)
Tanker (TA)	Fort Mifflin (Sun)	641 + 6710 ∗ BETA(2.66, 9.98)
	Paulsboro (Valero)	563 + ERLA(334, 3)
	Eagle Point (Sun)	524 + GAMM(442, 2.25)
	Delaware City (Valero/Premcor)	36 + ERLA(334, 5)
	Wilmington oil pier	930 + 2630 ∗ BETAQ.44, 2.88)

5.8. Terminal operations

Terminal operations in the River are described via the total time spent by a vessel in a terminal which is referred as the holding time in the model. As far as the model is concerned, the holding time is to represent vessel's entire operation at a terminal. This study does not go into details of terminal logistics since it would not be possible to handle details of all the terminals in the simulation model. The model is only concerned with the berth holding times of vessels at each terminal. Holding time represents the duration between entrance and departure of a vessel from a terminal including preparation, loading, unloading, and other processes that vessels typically go through at a terminal.

Vessels visiting terminals are assigned a holding time from a random probability distribution in the beginning of their trip to a terminal. Holding time distributions are determined based on statistical analysis of historical data obtained from Maritime Exchange [1] and they are vessel-type and terminal specific in order to reflect characteristics of different cargo specific operations. That is, for each vessel type a holding time table is prepared which has probability distributions for all possible terminals to be visited. Table 4 shows an example of such a table for BU and TA vessels for some selected terminals.

Once vessels dock at their reserved berths in a terminal, operation starts and continues through the holding time. When the operation is completed, a vessel makes its following reservation (if any) and departs from the terminal.

6. Model outputs

Model outputs are statistics regarding port performance collected during and at the end of each simulation run. These statistics can be collected as time-averaged statistics or vessel-averaged statistics presented in the form of the average, minimum, maximum and 95% confidence interval. In terms of model outputs, 'port' term is used to signify overall DRB terminal facilities.

Vessel-averaged statistics (averaged over entity values) are:

- Annual port calls per vessel type (total number of visits to DRB).
- Port times per vessel type (total time spent in DRB).
- Terminal calls per vessel type.
- Annual anchorage visits per vessel type.
- Anchorage delays per vessel type.

Time-averaged statistics are:

- Terminal/berth utilizations.
- Anchorage occupancy (number of vessels in anchorage at any time).
- Port occupancy (number of vessels at berths at any time).

Delaware River and Bay area is a tri-state region and accordingly different parts of the River are under the jurisdiction of different states. Furthermore, the landscape is such that bulk handling is more significant in New Jersey whereas container activity is heavier in Pennsylvania and oil and petroleum handling operations are somewhat balanced in all three states. Thus, the model also produces state-specific output [6]. The results based on states of New Jersey (NJ), Pennsylvania (PA) and Delaware (DE) are also listed for each year in cases of increasing vessel arrivals for Bulk, Cargo Containers, General Cargo, Parts Container, Vehicle and Tanker vessel types.

7. Verification & validation

The model is verified in several steps to check if it is working the way it is intended to. First of all, the model is developed in stages and through sub-models in which each stage is individually examined. Another method used throughout the model development phase is the tracing approach. Via tracing, a detailed report of entity processing can be compared with manual calculations in order to check if the logic implemented in the model is as intended. Animation is another useful tool for verification and validation purposes. Through animation, operation of the overall system can be followed as well as synchronization of events can be observed and verified.

For validation purposes, several tests are performed and various key performance measures are observed to see if they are close to their counterparts in reality [7,8]. Lastly, as a conclusive test of validation, the model outputs are compared to the real system data on hand. The simulation results of one replication for 30 years representing the current situation in DRB are compared to the observations of the years between 2004 and 2008. These observations are based on port calls and port times, anchorage calls and delays, and terminal utilizations as shown in Table 5 and Figs. 7 and 8. Note that, the number of vessels in the system stabilizes within a couple of days when simulation starts with an empty system. For instance, 30-year averages are not impacted by the transient system behavior when a 30-day warm-up period is selected. Consequently, warm-up is ignored in the model.

Port times include all holding times at the visited terminals, travel times and anchorage delays from entrance to exit of a vessel in the system. Thus, it is the most meaningful comparison for validation purposes. Table 5 shows average observed port times and the estimated port times with their 95% confidence intervals. Notice that, all average port time figures lie within 6% difference from the actual value. On the other hand, since the port call for each vessel type is generated using a distribution or process specific to that vessel type, discrepancy from the actual data is only due to randomness. Finally, aggregate figures of the average port time and port calls indicate that the actual system is also well represented within the simulation without regard to specific details or exceptions.

Terminal berth utilizations shown in Fig. 7 are other measures that are used to test the validity of the model. Among more than 40 terminals in the system a few of them have berth utilizations around 4% difference while rest of the terminals lie around 2% difference from the actual utilizations. 95% confidence intervals are also obtained for terminal utilizations.

Table 5
Port times and port calls.[a]

Vessel type	Actual data 04–08		Simulation	
	Average port time per vessel (min)	Average no of vessels per year	Average port time per vessel (min) (half width 95% C.I)	Average no of vessels per year
Bulk (BU)	5597.25	423.2	5686.9(±130.35)	416.9
Containership (CC)	1975.85	475.8	1980.4(±43.89)	463.2
Chemical (CH)	3687.37	70.6	3604.3(±139.76)	71.6
Non-flammable product (NP)	2501.35	50.8	2494.4(±43.64)	50.5
General cargo (GC)	3937.95	262.6	3715.8(±62.25)	260.9
Parts container (PC)	5072.30	66.2	5055.0(±180.84)	67.0
LPG (PG)	6030.96	31.4	6307.5(±335.34)	32.7
Passenger (PR)	1246.05	32.6	1247.3(±16.73)	32.0
RO–RO container (RC)	368.89	63.8	366.24(±33.51)	65.4
Refrigerated (RF)	4142.07	337.2	4171.9(±67.52)	336.1
RO–RO (RR)	3022.94	85.8	3076.0(±139.01)	88.8
Tanker (TA)	5011.79	921.2	4945.4(±109.08)	924.6
Vehicle (VE)	712.84	300.8	730.96(±21.12)	305.1
Tug boat (TG)	4443.93	667.0	4191.7(±84.46)	675.5
Overall	3898.43	3789.0	3839.53(±39.82)	3790.5

[a] Actual Tug Boat data are based on 2004 only..

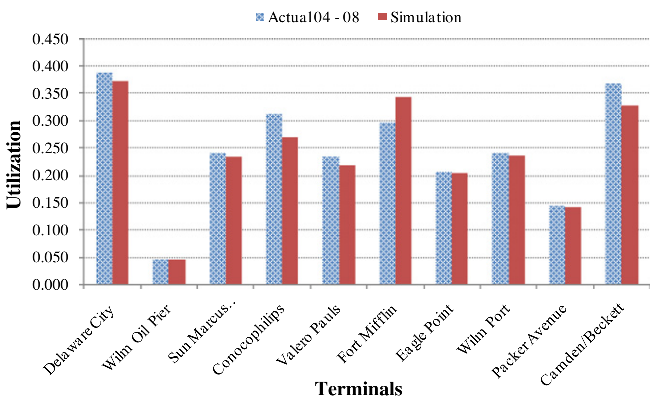


Fig. 7. Selected terminal utilizations per berth.

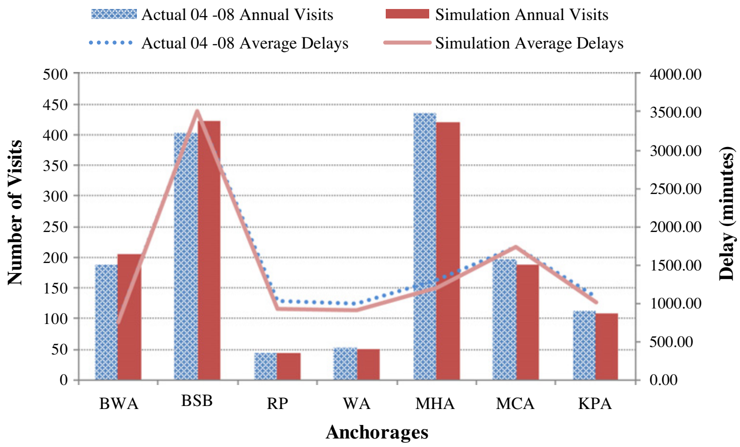


Fig. 8. Annual anchorage visits and average delays per visit.

Anchorage visits and delays are of critical importance in the validation process since these visits are mostly based on decisions rather than random events in the model. Therefore, less variation in these figures indicates robustness of the model. As seen in Fig. 8, annual visits and average delays in all anchorages are highly close to their actual counterparts. In addition to the aggregate results given here, vessel-type-specific results are also collected and found to be highly close to the actual values in most of the cases.

As a result of these comparisons between the actual data and simulation results, the simulation model built to mimic the vessel traffic in Delaware River and Bay is considered to have close representation of the actual system to perform the scenario analysis on the issues mentioned earlier.

8. Scenario assumptions

The scenario analysis presented in this paper is focused on investigating effects of deepening on port performance measures based on several assumptions. For this purpose, major assumptions of increase in the vessel traffic through potential trade growth in Delaware River, deepening the main channel and dredging berths at some specified terminals are considered and deployed in different scenarios. In deployment of these assumptions into scenarios the data provided by the Comprehensive Economic Reanalysis Report of Delaware River Main Channel Deepening Project, prepared by the US Army Corp of Engineers (USACE) are used [4].

The scenarios presented in this paper are as follows:

A. Current scenario (results given in the validation section).
B. Current scenario with 30-year trade growth.
C. Deepen & dredge with 30-year trade growth.
D. Deepen & dredge and shift to a fleet of larger vessels with 30-year trade growth.

The major assumptions used in these scenarios are described below in detail.

8.1. Trade growth

Future trade forecast for Delaware River port system is investigated in the deepening analysis report of the USACE [4]. This report displays the projected growth in tonnage from 2000 to 2050 with ten year increments. Based on this analysis the ten year increase rates are decomposed into years for each ten year period as given in Table 6, thus future vessel arrival patterns for the next 30 years are estimated annually and incorporated for almost all vessel types in the model. Note that the rates given in the table are annual and are compounded throughout 30 years.

Table 6
Annual percentage increase in arrival rates by vessel type.

Vessel types	First 10 years	Second 10 years	Third 10 years
TA, CH, NP, PG	0.4470	0.3792	0.3038
BU, GC, RF, RR, VE	2.3229	1.0119	0.3708
CC, PC, RC	4.5424	2.5205	1.2771

With this assumption, it is expected to observe higher terminal and anchorage utilizations, increase in the lightering activity and possible increase in the tidal delays and anchorage waiting times.

8.2. Deepening the main channel and dredging terminal berths

As described earlier, the deepening project will increase the depth of the main channel from 40 to 45 ft from the Delaware Bay entrance to the Philadelphia Harbor, PA and to Beckett Street Terminal, Camden, NJ and will provide 45 ft depth at the MHA. Terminals in this region might benefit from the deepening project by dredging nearby their berths. Based on the USACE report, berth deepening data for dredge-designated terminals given in Table 7 below are incorporated into the scenarios operating under this assumption.

As a result of increased depth in the main channel and in the terminals, lightering needs of tankers will be lesser. However, this may cause increased holding times at terminals for tankers bringing more cargo. In order to represent this increase, a ratio is used based on the tonnage difference being carried to the terminal and holding time is increased.

Along with deepening of the main channel, some regulations controlling the navigation in the River are needed to be revised. Since deepening concerns the River up to Philadelphia region tide regulations regarding the Lower River are relaxed by 5 ft in the model. Therefore, inbound tidal delays in BWA and outbound tidal delays especially in the MHA are expected to be reduced.

In this assumption, it is anticipated to see less lightering activity in the BSB due to increased depth in the main channel to accommodate deeper draft vessels. However, vessel types other than tankers are not expected to see much navigational benefits since there is no change in the vessel fleet or in the cargo tonnages of the vessels.

8.3. Shift to a fleet of larger vessels

Under the deepening conditions, a deeper channel would allow some commodities to be brought in on larger vessels, thereby reducing the total number of calls required to move the current volume of commodity. However, shift to a fleet of larger vessels can only be practical for those terminals deepening some of their berths in order to accommodate larger vessels. According to the USACE report, the benefits are identified especially for tankers, container ships and dry bulk vessels which correspond to TA, CC, BU, GC, PC and VE vessels in the model. Therefore, a detailed analysis should be performed to estimate a new configuration of larger vessels of the aforementioned types visiting dredge-designated terminals.

For each vessel type visiting a dredge-designated terminal, a new fleet of larger vessels is generated by increasing the draft of each vessel by 5 ft and reducing the total number of vessel visiting the terminal while preserving the total tonnage coming to the terminal. When there is increase in cargo tonnage for a particular vessel due to longer durations of loading/unloading operations it is assumed that holding time is also increased. Due to lack of data on hand, the holding time of the

Table 7
Terminal berth dredging plans [4].

Terminal/company	Berth	Depth (ft.)
Fort Mifflin (Sun)	A	38 → 45
	B	37 → 45
Marcus Hook (Sun)	3C	40 → 45
	3A	Remains 39
	2A	Remains 37
	3B	Remains 17
Paulsboro (Valero)	Berth # 1 (tanker berth)	40 → 45
	Berth # 2	Remains 30
Eagle Point (Sun)	Berth # 1	Remains 34
	Berth # 2	40 → 45
	Berth # 3	40 → 45
Conoco Philips	Berth # 1	38 → 45
Valero/Premcor Delaware City	Berth # 1	→ 45
	Berth # 2	→ 45
	Berth # 3	→ 45
Wilmington oil pier	Liquid bulk berth	38 → 45
Packer Avenue	5 Front berths	40 → 45
	The bottom berth	Remains 40
Beckett Street	Berth # 4	40 → 45
	Berth # 3	Remains 35
	Berth # 2	Remains 30
Wilmington port	All berths in Christina River	38 → 42

new fleet is increased by the same critical ratio which is used to reduce the total number of vessels. The maximum draft and gross tonnage relation, which is assumed to be in parallel with the underway draft and cargo tonnage relation, is used to calculate the critical ratio to reduce the number of vessel calls and increase the holding time. This procedure is repeated for the same vessel type visiting all dredge-designated terminals, and the new total number of vessels is obtained and arrival rate of the vessel type is adjusted accordingly. At the end, interarrival time distribution, itinerary matrix, holding time and underway draft distributions are revised. A formal description of this procedure is as follows:

Step 1: Let *i: index for vessel*
d_i: *draft of vessel i*
$GT_{i,k}$: *gross tonnage of vessel i arriving at terminal k*
$HT_{i,k}$: *holding time of vessel i at terminal k*
$GT_{i,k} = f_k(d_i)$ as defined by a regression model using historical data over vessel type *V*
Step 2: Select vessel type set *V* // e.g. vessel type "BU"
Step 3: Select dredge-designated terminal *k* // e.g. Camden Marine Terminal
Step 4: Let N_k = *total number of vessels arrived at terminal k* // from historical data
Step 5: Let $S_k = \sum_i^{N_k} GT_{i,k}$ // total tonnage received at terminal *k*
Step 6: Set $d_i^+ \leftarrow d_i + 5ft$ for all $i \in N_k$ // increase vessel draft by 5 ft
Step 7: Set $GT_{i,k}^+ \leftarrow f_k(d_i^+)$ // set increased tonnage for vessel *i* arriving at terminal *k*
Step 8: Let $R_k^* = \frac{\sum_i^{N_k} GT_{i,k}^+}{S_k}$ // critical ratio R_k^* for increased tonnage at terminal *k*
// R_k^* is to be used to reduce the number of vessels in *Step 9*
Step 9: Set $N_k^- \leftarrow \frac{N_k}{R_k^*}$ // corresponding reduced total number of vessels for terminal *k*
Step 10: Set $HT_{i,k}^+ \leftarrow HT_{i,k} \times R_k^*$ // increased holding time per vessel at terminal *k*
Step 11: Go to *Step 3* until all dredge-designated terminals are done.
If done, go to *Step 12*.
Step 12: Modify overall vessel arrival rate to match the reduced number of arrivals at the port.
Step 13: Modify the itinerary matrix for vessel type *V* to match the reduced number of arrivals at terminals.
Step 14: Go to *Step 2* until all vessel types are done.

A numerical example can be given as follows. There are 341 BU vessels visiting Camden/Beckett, NJ terminal in the actual data between 2004 and 2008. Total gross tonnage of these vessels is 8,226,031. When each vessel's draft is increased by 5 ft, using maximum draft and gross tonnage regression equation on each vessel, the total gross tonnage would be 11,118,534. Consequently, the required number of vessels to carry the original tonnage can be reduced by using the critical ratio of 1.35 (which is 11,118,534/8,226,031) resulting in 253. Accordingly, as an approximation (especially due to lack of data) the same critical ratio is used to increase holding time for each vessel for this terminal. For other dredge-designated terminals (e.g., Packer Avenue, PA and Wilmington Port, DE) BU vessels are visiting, the same procedure is applied.

This assumption is important in order to test if there is any navigational benefit in terms of port times and anchorage usage when there is less number of vessels coming to the River. Besides, it is critical to make this observation with the trade growth assumption in effect in the River.

9. Results of scenario analysis

The results of the current scenario representing the current situation in the River based on actual data between years 2004 and 2008 are given in the validation section. The other three scenarios described above are built on top of the current scenario and the simulation runs of these three scenarios are made for 30 years, each with 100 replications. In these runs, due to year-to-year growth patterns, simulation results are obtained for each year separately. In addition to the standard output defined, detailed annual and state based (DE, NJ and PA) vessel statistics are collected for TA, CC, BU, GC, PC and VE vessel types for each scenario. Nevertheless, due to their significance in the system only TA, CC, BU and GC vessel types are considered in the scope of this paper and aggregate (non-state based) results are presented accordingly.

The number of replications is decided based on the tests as depicted in Fig. 9 where the average port time for tankers stabilizes after around 30 replications, nevertheless 100 replications is selected for consistency. Furthermore, Fig. 9 also shows that tests with 30-day warm-up period do not show any significant difference when compared to the cold start case for annual results.

Port times, port calls, anchorage visits and anchorage delays are reported for the first year and for the 30th year after they are averaged over 100 replications. First year values are useful to understand the impact of deepening and shifting to a fleet of larger vessels since the effect of trade growth is not observed in the first year. Therefore, first year results of the growth scenario (having same results with the current scenario given in the validation section) represent the current situation in

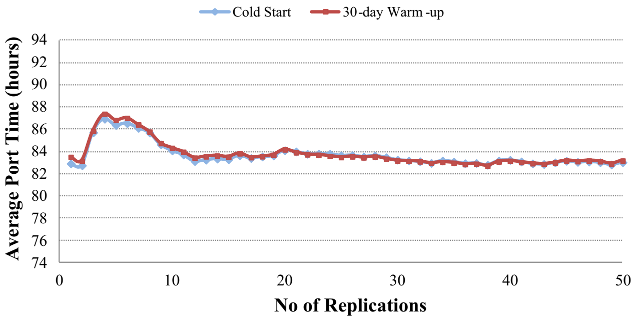


Fig. 9. Average port time (in hours) for tankers in the growth scenario (for the first year) averaged over replications with cold start and 30-day warm-up cases.

DRB and constitute a basis for the scenario comparisons. The 30th year results are given due to increase of vessel arrivals as a result of trade growth, thus these results help us to understand future effects of deepening & dredging and shifting to larger vessels.

Port times and port calls are considered to be the most important measures to observe and understand the effects of major assumptions among the scenarios considered. On the other hand, a new measure is defined as port time per kiloton brought to the River where kiloton is a reference to 1000 units in gross tonnage. This measure is important to see if there is a navigational benefit when there is a shift to a fleet of larger vessels since total tonnage coming to the River is same in all scenarios.

The results of the scenarios with their 95% confidence intervals based on 100 replications are given in Table 8 for the first year of the simulation runs. As seen in the table, port times are slightly decreased with deepening in Scenario C. These decreases are found to be statistically significant (through two-tail tests with a 5% significance level) only for tankers due to less lightering activity. Other vessel types mostly benefit from lesser tidal delays. As expected, bringing larger vessels in Scenario D increases port times since they spend more time at terminals. In this case, port time per kiloton experiences slight increases, except for container vessels, indicating that there is no gain in terms of port times when the total cargo handled is fixed. This reveals that CC vessels benefit from deepening which is due to ample capacity for these vessels in the River, and this benefit is found to be statistically significant.

Table 8
First year port results with 95% confidence intervals.

Scenarios – first year results	Outputs	Vessel types			
		BU	CC	GC	TA
Scenario B Growth	Average port time per vessel (h)	93.17 ± 0.99	32.72 ± 0.31	63.51 ± 0.66	82.75 ± 0.95
	Average no. of vessels per year	419 ± 4	465 ± 4	260 ± 3	917 ± 6
	Average port time/Kton (h)	3.75 ± 0.04	1.36 ± 0.01	5.12 ± 0.06	1.57 ± 0.02
Scenario C Growth + Deepen	Average port time per vessel (h)	92.43 ± 1.02	32.14 ± 0.25	62.63 ± 0.72	71.10 ± 0.48
	Average no of vessels per year	416 ± 5	463 ± 3	262 ± 3	919 ± 6
	Average port time/Kton (h)	3.72 ± 0.04	1.34 ± 0.01	5.05 ± 0.06	1.35 ± 0.01
Scenario D Growth + Deepen + larger vessels	Average port time per vessel (h)	103.97 ± 1.45	37.01 ± 0.36	69.07 ± 1.00	98.48 ± 1.34
	Average no of vessels per year	383 ± 4	378 ± 3	243 ± 3	772 ± 4
	Average port time/Kton (h)	4.04 ± 0.06	1.31 ± 0.01	5.18 ± 0.07	1.62 ± 0.02

Table 9
30th Year port results with 95% confidence intervals.

Scenarios – 30th year results	Outputs	Vessel types			
		BU	CC	GC	TA
Scenario B Growth	Average port time per vessel (h)	104.58 ± 1.43	33.72 ± 0.22	68.97 ± 0.82	91.42 ± 1.67
	Average no of vessels per year	610 ± 5	1049 ± 5	378 ± 3	1031 ± 6
	Average port time/Kton (h)	4.21 ± 0.06	1.41 ± 0.01	5.58 ± 0.07	1.73 ± 0.03
Scenario C Growth + Deepen	Average port time per vessel (h)	103.12 ± 1.57	33.40 ± 0.25	69.82 ± 0.86	72.36 ± 0.48
	Average no of vessels per year	612 ± 5	1051 ± 6	379 ± 4	1027 ± 6
	Average port time/Kton (h)	4.15 ± 0.06	1.39 ± 0.01	5.60 ± 0.07	1.37 ± 0.01
Scenario D Growth + Deepen + Larger vessels	Average port time per vessel (h)	124.47 ± 2.63	38.74 ± 0.28	79.45 ± 1.26	111.03 ±2.48
	Average no of vessels per year	559 ± 5	854 ± 5	353 ± 4	878 ± 5
	Average port time/Kton (h)	4.83 ± 0.10	1.37 ± 0.01	5.96 ± 0.10	1.81 ± 0.04

Table 9 shows the results for the 30th year of the simulation runs after they are averaged over 100 replications. These results could be interpreted as the maximum values to be observed towards the end of the simulation due to growth. Compared to the first year within Scenario B, all port times are increased with the container vessels having the least increase although their port calls are doubled. This is also due to ample capacity in container terminals in the River. Furthermore, tankers seem to benefit even more when the channel is deepened in Scenario C. When there is a shift to larger vessels, only container vessels improve their port times per kiloton measure compared to Scenario B, in a statistically significant manner. In Scenario D, all port time per kiloton values are increased compared to their first-year counterparts since the total berth capacity in the port remains the same even though there are more vessels calling.

Anchorage visits and delays are other important measures to understand vessel activity and waiting capacity in the main channel of DRB. The effect of scenarios on inbound tidal delays can be seen through the observations for the BWA. The effects on outbound tidal delays and waiting for terminal berth availability in other major anchorages (Wilmington, Marcus Hook, Mantua Creek and Kaighn's Point) are aggregated in the results as four anchorages.

First year results of the scenarios are given in Table 10. All scenarios have the same tidal delays in the BWA since these scenarios do not have impact on the delays due to tide or (random) waiting due to other reasons. However, in Scenario C, the BWA visits significantly decreased while in Scenario D it is slightly increased compared to Scenario C due to arrival of larger vessels.

In Scenario C with deepening, since there is more depth in the main channel, outbound vessels are less affected by tide so visits to four major anchorages decreased. However, in tankers and to some extent in bulk vessels, average anchorage delays seem to increase but this is because small tidal delay values (compared to waiting for terminals) lost their significance in the new average.

In Scenario D, vessel calls in four major anchorages seem to be similar to the one in Scenario C but anchorage delays are mostly increased. This is because larger vessels stay longer in terminals and that leads to longer delays in anchorages despite fewer vessels are coming to the system.

Anchorage results as they are observed in the 30th year are shown in Table 11. Compared to the first year results, in BWA there is significant increase in the number of visits but no change in delays. In the four major anchorages, both delays and

Table 10
First year anchorage results (delays and visits).

Scenarios – first year results		Outputs	Vessel types			
			BU	CC	GC	TA
Scenario B	BWA	Average delay per vessel (h)	14.74	8.28	7.16	12.02
Growth		Average no of visits per year	60	9	10	89
	4 Anchorages	Average delay per vessel (h)	34.49	9.24	18.83	13.01
		Average no of visits per year	108	19	49	368
Scenario C	BWA	Average delay per vessel (h)	13.73	0.00	7.40	11.95
Growth + Deepen		Average no of visits per year	40	0	8	41
	4 Anchorages	Average delay per vessel (h)	38.04	9.83	18.60	16.34
		Average no of visits per year	96	18	47	335
Scenario D	BWA	Average delay per vessel (h)	14.12	8.17	7.22	12.10
Growth + Deepen + Larger vessels		Average no of visits per year	49	6	10	78
	4 Anchorages	Average delay per vessel (h)	54.22	9.67	33.85	17.77
		Average no of visits per year	96	16	42	321

Table 11
30th Year anchorage results (delays and visits).

Scenarios – 30th year results		Outputs	Vessel types			
			BU	CC	GC	TA
Scenario B	BWA	Average delay per vessel (h)	14.83	8.44	6.85	12.18
Growth		Average no of visits per year	88	19	14	99
	4 Anchorages	Average delay per vessel (h)	53.86	15.00	34.30	13.82
		Average no of visits per year	216	77	97	425
Scenario C	BWA	Average delay per vessel (h)	13.83	0.00	7.27	12.19
Growth + Deepen		Average no of visits per year	59	0	13	46
	4 Anchorages	Average delay per vessel (h)	56.06	16.12	35.18	17.11
		Average no of visits per year	198	73	97	389
Scenario D	BWA	Average delay per vessel (h)	14.15	8.56	7.74	12.05
Growth + Deepen + Larger vessels		Average no of visits per year	71	13	13	87
	4 Anchorages	Average delay per vessel (h)	95.56	17.69	63.34	18.41
		Average no of visits per year	178	56	83	338

Table 12
Big stone beach anchorage results for tankers.

Scenarios	Outputs	First year	30th Year
Scenario B	Average delay per vessel (h)	59.77	77.80
Growth	Average no of visits per year	396	443
Scenario C	Average delay per vessel (h)	42.80	44.29
Growth + Deepen	Average no of visits per year	237	263
Scenario D	Average delay per vessel (h)	66.79	95.59
Growth + Deepen + Larger vessels	Average no of visits per year	285	326

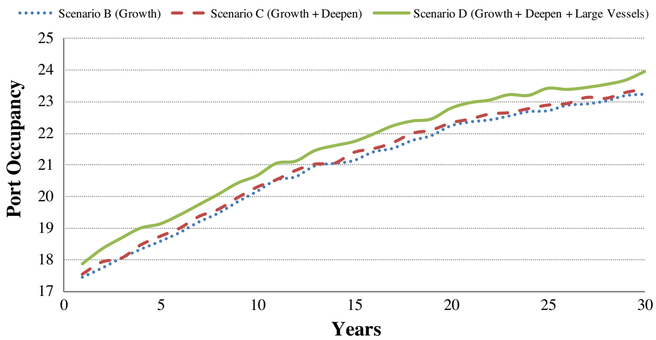


Fig. 10. Port occupancy in the River observed in the 30-year planning horizon.

visits are significantly increased. This shows a potential capacity issue for the major anchorages in the River for the years to come in the planning horizon. In Scenario C, again there is a decrease in the number of visits to four anchorages since vessels are less affected by tide and thus, tidal delays lost their significance in the new average delays which are higher now. In Scenario D, the four anchorages visits are decreased but delays are increased for bulk and general cargo vessels. This increase is due to longer holding times of larger vessels in terminals that in turn affect waiting in the anchorages.

As mentioned before, tanker operations is the dominant activity in the DRB port system and according to the results above tankers are benefiting the most from the deepening (Scenario C) in the River in terms of reduced port times. This is essentially due to less lightering as a consequence of deepening. Table 12 shows the number of visits and average delays for tankers in BSB mainly resulting due to lightering activity. As seen in the table, deepening the River decreases number of visits to the BSB and even the delays. However, bringing larger vessels moderately increases the number of visits and significantly increases the delays.

Considering more than 40 terminals and around 100 berths in the DRB port system, port occupancy is an important measure to show how busy the port is at any point in time. This measure shows the overall vessel density (number of vessels) at terminal berths in the port and can be thought of as an overall utilization measure for the entire port. Fig. 10 shows the port occupancy throughout the 30-year period for the three scenarios. While the current value is around 17.5, it reaches around 23.5 showing growth in 30 years. This trend is affected by vessel arrival rates and terminal holding times resulting in a similar behavior in all scenarios. However, due to longer holding times in Scenario D, the port occupancy is slightly higher than in other scenarios. This observation is in parallel with slightly higher port time per kiloton values discussed earlier.

10. Conclusion

In this paper, simulation modeling of vessel traffic in Delaware River and Bay is presented with an objective of investigating the impact of deepening on the navigational issues. The paper elaborates on the simulation model built, develops scenarios to perform an analysis on effects of deepening and discusses the results of the scenarios on navigational benefits.

The Growth Scenario (B) exhibits an increased usage of berths due to trade growth and the port seems to handle the additional load well in all vessel types. In this regard, port occupancy measure is critical to point out overall utilization in the port in which the temporal behavior stresses the need for planning of port expansion in the future. Among others, container facilities better handled more vessels due to ample capacity in container terminals. Besides, tankers appear to benefit from deepening even more in the case of increased oil trade in the port.

The Deepening Scenario (C) verifies the anticipated benefits due to lesser tidal delays and lightering activity. Tankers benefit the most due to decrease in their port times that is around 14% in the first year and around 21% through the end of the 30-year planning horizon. Other vessels have minor gains (decrease) in their port times.

The Larger Vessels Scenario (D) investigates presumed benefits despite the intrinsic longer port times per vessel when there is a shift to a fleet of larger vessels. Therefore, in order to evaluate navigational efficiency, port time per kiloton measure is introduced since it represents the amount of time spent to handle a unit amount of cargo. Port time per kiloton shows statistically significant benefits for container vessels in larger vessels scenario whereas they show no navigational benefits for other vessels. However, port time per kiloton results in Scenarios B and D show that non benefit for tankers may be doubtful due to proximity of their means and magnitude of variances. Note that, these observations are very sensitive to holding time of vessels at terminals, specifically to the factor used in the model to increase holding time of larger vessels. In the case of improved scheduling practices and efficient handling of larger vessels at terminals, port time per kiloton measure will most likely exhibit navigational benefits possibly for all vessels.

Anchorage results verify the expected decreases in tidal delays both for inbound and outbound vessels and reduced lightering activity. Lightering activity results in the beginning years of the planning horizon reveal about 40% decrease in the Deepening Scenario (C) and 28% decrease in case larger vessels are used after deepening is completed. Furthermore, the Growth Scenario (B) shows the usage of major anchorages almost doubled in the long run when the total capacity in the port is kept the same, while deepening and shifting to a fleet of larger vessels help reduce anchorage calls to a certain extent. On the other hand, longer anchorage delays are also possible for larger vessels due to longer holding times at terminals.

This paper presents results on several aspects of navigational issues which impact transportation cost savings based on vessel and operational efficiencies. The findings suggest some navigational benefits for container vessels and tankers but no significant efficiency for bulk and general cargo vessels. However, this study does not cover potential reduction in operating costs due to lesser number of vessels and the economic benefits due to growth. In addition, note that categories of benefits identified for deepening includes improved safety on which reduced number of vessels sailing in the River has a positive impact.

At last, an important final product of this study is the simulation model itself, developed for Delaware River and Bay. It can be used to support decision making process in various areas of interest and to answer "what-if" questions since it enables experimentation with policies, operating procedures, decision rules or environmental changes. Besides, it is believed that the model provides a better understanding of the overall port system, interaction of system components and resources.

11. Further research

The simulation model developed in this study has various simplifications and assumptions about the real system. The major components forming the model structure are relying on the historical data. In this regard, the study is open to improvements in various areas especially in the vessel arrival processes and service processes at terminals, which are core components of the system. Besides, validity of the results presented in this study is dependent on the quality of the data on hand.

In this study, the vessel arrivals to the system are based on vessel types in which minor correlations are neglected in vessel generation processes. However, these processes can be based on terminals where each arrival stream aims at specific terminals, and terminal specific details can improve modeling the arrival processes. This way, scheduled arrivals to the specific terminals can help identifying the impact of individual vessel streams on anchorage delays and port times. Effects and modeling of negatively correlated vessel arrivals might be investigated in future studies as well.

Service processes at terminals which are referred to as the holding time in this study can be modeled in detail if and when data is available. This way, vessel particulars could be associated with the service process which may help testing different scenarios and may improve the analysis of shifting to a fleet of larger vessels. However in this study, the data on hand does not suggest a significant relation between holding time and vessel size, particularly underway draft (Fig. 11). This is somehow reasonable to observe in such a lumped data with observations including other factors affecting holding times of different vessels such as vessel light-loading, cargo type dependent operation times, maintenance related extra berth times and others.

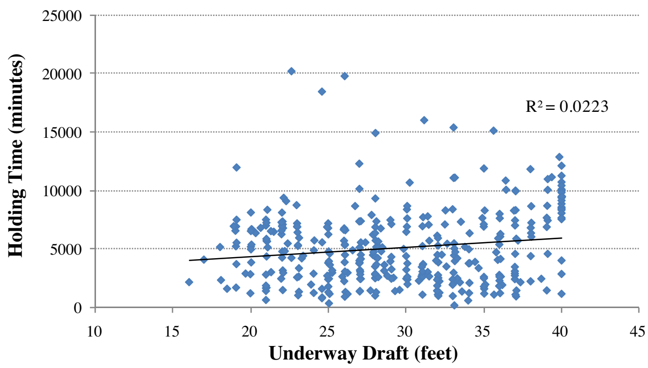


Fig. 11. Holding time versus Underway Draft of BU vessels at Camden Marine Terminal, NJ.

The model presented in this study is being used in the analysis of port expansion projects and investigating the effects of new terminals on the current vessel traffic in Delaware River. It is also being used in a comprehensive risk analysis study of the vessel traffic in the River.

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