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# RISK AND PERFORMANCE ANALYSIS OF PORTS AND WATERWAYS:

### THE CASE OF DELAWARE RIVER AND BAY

by

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#### ABSTRACT OF THE DISSERTATION

Risk and Performance Analysis of Ports and Waterways: The Case of Delaware River and Bay By OZHAN ALPER ALMAZ

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Delaware River is one of the major maritime arteries in the U.S. The port has a number of major petroleum refineries making it one of the most critical petroleum infrastructures in the U.S. Consequently, in addition to port performance issues, major safety vulnerabilities exist in view of the vessel traffic in the river carrying potentially dangerous cargo, dry cargo as well as passenger ships, among others.

In this research, several issues regarding the risk and performance analysis of ports and waterways are investigated through the case of Delaware River and Bay. The issues pertaining to Delaware River are common to many other ports and waterway systems. Thus, modeling and analysis approaches presented herein provide guidelines that can be implemented to other systems.

The dissertation presents a simulation model of the vessel traffic in Delaware River and Bay (DRB) involving all vessel types and all the port terminal facilities along the navigable river. The simulation model is built to be able to perform scenario and policy analyses, including investigation of the effects on port performance of deepening the main ship channel and dredging at terminals. The model is also used to examine the feasibility and the effects of port expansion projects, and to perform logistics and risk analysis in the DRB area.

A probabilistic risk model is developed using historical data and expert opinion elicitation for the unknown accident and consequence probabilities of various situations. The risk model is incorporated into the simulation model to be able to evaluate risks and to produce a risk profile of the entire river.

The important topic of vessel prioritization is studied using the simulation and the risk models. Vessel prioritization rules are used for entry into the river during recovery operations following a channel-closing event, and their impact on risk and port performance measures are evaluated.

Finally, vessel arrival processes at terminals are examined with reference to the real life practice at ports and waterways. These processes are characterized with one-dimensional point processes, and variation and correlation properties are investigated. The focus is modeling vessel arrivals with specific correlation properties to use in simulation studies.

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## DEDICATION

This dissertation is dedicated to the memory of my advisor, Tayfur Altiok

for all his support during my study

and inspiration to live such a fulfilling life

#### PREFACE

The study conducted in this dissertation has been presented and published in several conferences and journals. Below is the list of publications derived from this dissertation.

Almaz, O.A. and T. Altiok, 2012, "Simulation Modeling of the Vessel Traffic in Delaware River: Impact of Deepening on Port Performance", *Simulation Modeling Practice and Theory*, Vol. 22, pp. 146-165

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## **1. INTRODUCTION**

Delaware River has been a commercial maritime route for handling import and export of raw and manufactured goods for more than three centuries. Today, it has more than 40 port facilities with their associated businesses located 60 to 100 miles up the River with about 3,000 vessels visiting each year.

The Delaware River region has proximity to the densest population base in the U.S. Twenty-seven million people live within 100 miles, and 90 million within 500 miles, giving its ports a massive consumer market. Approximately 65% of the region's cargo tonnage is petroleum. Other major cargoes are steel, wood products, and perishable items such as fresh fruit, nuts, cocoa beans, and meat products. Major ports are Wilmington, Chester, Philadelphia, Camden, and Trenton, with major petrochemical facilities at Delaware City (DE), Paulsboro (NJ) and Marcus Hook (PA). Figure 1.1 shows a detailed map of Delaware River and Bay (DRB) which illustrates all terminals, anchorage areas, important regions in the river as well as entrance and exit points.



Figure 1.1 - Delaware River and Bay

The Delaware River Main Channel (DRMC) affords deep draft (40-foot) navigation for nearly 110 miles, from the mouth of Delaware Bay to Trenton, NJ. The Delaware River shoreline has a number of major petroleum refineries that handle nearly 1 million barrels of crude oil per day, as well as other chemicals associated with the refining process. The incoming traffic brings around 12% of the nation's crude oil imports making the port one of the most critical petroleum infrastructures in the U.S. Including the ports of Philadelphia, South Jersey and Wilmington, DE, Delaware River is one of the largest general cargo port complexes in the nation. With one third of the entire U.S. population living within 5 hours of the Port of Philadelphia, Delaware River and its surrounding facilities are critically important to the nation's economy (Maritime Commerce in Greater Philadelphia, 2008). In this regard, port performance issues, as well as major security vulnerabilities, are present because traffic in the channel carries combustible cargo (oil and LP gas), dry cargo (bulk and container), in addition to passenger ships, among others. Thus, the magnitude and nature of the traffic render the area a tempting potential target for terrorist activity, and closure for even a few days would result in serious consequences in the region.

As water traffic is expected to increase during this decade and beyond, the risk of a major vessel collision can be expected to rise. Indeed, the U.S. Energy Information Administration expects U.S. total crude oil production to average 6.3 million barrels per day in 2012, with an increase of 0.6 million barrels per day from the previous year, reaching the highest level of production since 1997. In addition, it is projected that U.S. domestic crude oil production will increase to 6.7 million barrels per day in 2013. (Short-

Term Energy Outlook, August 2012). Furthermore, the world LNG trade sector is in a period of large-scale expansion with a 22% jump in trade volume in 2010 compared to 2009. The world fleet of LNG carriers has expanded from 195 vessels in 2005 to the 2010 total of 360. (World LNG Report, 2010). These facts translate into significant increases in projected numbers of crude oil, LPG and, potentially LNG carriers and corresponding port calls required to meet future demand. In particular, the DRMC is expected to experience increased vessel traffic in all categories with oil, chemical, LPG and LNG carriers giving rise to concerns for high risk incidents. Currently, the DRMC is being deepened to 45 feet to accommodate larger vessels into various port terminals in the river.

The SAFE Port Act of 2006 (PL 109-711) requires Area Maritime Security Plans to include a salvage response plan intended, inter alia, to ensure that commerce is quickly restored to U.S. ports following a transportation security incident. Accordingly, this motivates the need to study and analyze the risks inherent in DRB vessel traffic, in order to develop a post incident recovery strategy.

In this regard, the project, entitled "Modeling and Analysis of the Vessel Traffic in the Delaware River and Bay Area: Risk Assessment and Mitigation" was initiated in July of 2007 by the Maritime Resources Program in New Jersey Department of Transportation in cooperation with the Area Maritime Security Committee (AMSC) and the U.S. Coast Guard Sector Delaware Bay. The project was carried out by the Laboratory for Port Security (LPS) of the Center for Advanced Infrastructure and Transportation (CAIT) at Rutgers, The State University of New Jersey. Project goals were:

- Development of a simulation model of the maritime traffic in Delaware River,
- Analysis of the impact of deepening on port performance,
- Risk analysis of the maritime traffic,
- Analysis of the resumption of trade after reopening.

The project has 4 parts, each focusing on one of the goals mentioned above. A detailed large-scale simulation model is developed in Part 1 and used for the analysis of impact of deepening on port performance in Part 2, for risk analysis in Part 3 and finally for vessel prioritization in Part 4. A 30-year planning horizon is used in the project.

The project is described under Maritime Domain Awareness projects in the Strategic Risk Management Plan (Tetra Tech, 2008) of the Area Maritime Security Committee of the U.S. Coast Guard Sector Delaware Bay. It is also described in the section entitled Current Port-Wide Risk Reduction Measures (Section 4.4.6). In this plan, it is recommended that the results of the project be used to establish an Aid-to-Navigation (ATON) plan in the section entitled Systems Interdependencies and Resilience (Section 5.5.3.1), to establish vessel prioritization (Systems Interdependencies and Resiliency – Section 5.6.2) and for Resiliency and Continuity Exercise Program in the section entitled Risk Reduction and Gap Analysis for Vulnerabilities (Section 6.1.15). Finally, it is recommended that the results be used for cascading economic effects in the section entitled Mitigation Measures (Section 8.2.4).

This dissertation describes the modeling and analyses performed for the aforementioned project, and elaborates upon relevant topics of theoretical and practical interest. The outline of the dissertation is summarized below.

In Chapter 2, a simulation model is discussed which mimics the vessel traffic in the DRMC along the navigable river from the Cape Henlopen / Cape May entrance up to Trenton. It incorporates all the cargo vessels as well as all the terminals operating in the river using the data from the Maritime Exchange for the Delaware River and Bay for the years between 2004 and 2008. The model maintains the navigational recommendations of the Coast Pilot (2008) as well as the thought processes used by the pilots in bringing vessels to anchorages. Vessel arrival patterns and frequencies, travel times, anchorage delays and dock holding times at terminals are analyzed and included as part of the model's logic. Finally, details of lightering operations at the Big Stone Beach anchorage are also included.

The model is built using the Arena simulation tool of Rockwell Software to perform scenario and policy analyses on various issues as well as to support a comprehensive risk analysis of the DRB area. It is also aimed to be used to examine feasibility and the effects of port expansion projects which may include construction of new terminals, installation of new infrastructure facilities or energy projects such as off-shore wind farms. It is verified, and validated using the aforementioned data, and is an accurate representation of the traffic in the river. It produces statistical estimations for vessel port times, anchorage delays, delays at the entrance, terminal berth utilization and the overall port occupancy. The details of the modeling effort are expanded in Chapter 2 and provide a road-map to develop a similar tool for other ports and waterways for the same objectives.

Deepening of the DRMC has been debated over several years due to the current expansion of the Panama Canal. The plan consists of deepening the channel to 45 feet below mean water level and provision of an anchorage with a depth of 45 feet at Marcus Hook. The anticipated benefits include reduced costs of transportation due to reduced lightering and light-loading, and the use of larger vessels resulting in cost reduction per ton of cargo according to the Comprehensive Economic Reanalysis Report of Delaware River Main Channel Deepening Project, prepared by the U.S. Army Corp of Engineers (USACE, 2002). At the end of Chapter 2 the simulation model is used to analyze the impact of deepening on port performance in the river measured by vessel port times, anchorage delays and terminal berth occupancies. Navigational efficiencies may include shortened port time per vessel call, lesser anchorage delays and lesser tidal delays, among others. To analyze these possible efficiencies, scenarios are generated considering increase in vessel arrivals due to trade growth, deepening the river by 5 feet, and changing the vessel profiles. Growth projections and relevant data are provided by USACE (2002). To the best of our knowledge no similar work is located in literature. Thus, a main contribution of this analysis is to underscore the need for such a study during dredge/deepening planning processes in any port or waterway system.

In Chapter 3, an extensive risk analysis is carried out by incorporating a risk model into the simulation model developed. A probabilistic risk model is developed considering possible accidents as suggested by the historical data in DRB. Safety risks are considered as a result of accidents such as collision, allision, grounding, fire/explosion, sinking and oil spill. The historical accident data obtained from the U.S. Coast Guard (USCG) showed human error, propulsion failure, electrical/electronic failures, steering failures and failures of other systems such as hull structure and cargo control systems as the primary accident instigators. Finally, the historical records suggest human casualties, environmental damage and property damage as potential consequences.

An expert opinion elicitation process helped to estimate unknown accident and consequence probabilities lacking in the historical data for various situations. The elicitation process was carried out surveying regional experts, mostly with USCG backgrounds. This required surveying using questionnaires in order to collect information on the influence of situations such as day/night times, tide, vessel types, number of vessels and seasons on the occurrence of instigators, accidents and consequences. Consequences of these events are estimated as dollar values. Accident probabilities, expert opinions and consequence values are all combined in an overall safety risk measure where the risk is expressed in dollar terms.

The DRMC was divided into six zones and the overall safety risk measure is evaluated for each zone, creating a risk profile for the entire river. This makes it possible to evaluate and compare risks of different zones and to produce supporting evidence for various risk mitigation initiatives.

Scenario analyses are developed in order to measure the effectiveness of risk mitigation ideas and to investigate effects of deepening and bringing larger vessels on the risk profile of the river. The procedure presented here can be adapted and used in risk assessment study of other systems of interest as well.

The important topic of vessel prioritization while resuming trade following a channelclosing event is studied in Chapter 4. Through vessel prioritization, we are concerned with the resumption of trade which is the final stage of recovery from an incident. Again using the simulation model and the risk model, this part focuses on vessel prioritization rules that can be used for entry into and exit from the river during recovery operations and to evaluate their impact on port performance as well as risk performance.

In November of 2004, a major oil spill occurred when the 750-foot tanker M/V Athos I struck a submerged anchor in Paulsboro. The resulting breach in the ship's hull spilled approximately 265,000 gallons of crude oil into the river. The entire channel was closed to traffic for three days. This was one of the most significant incidents in the history of Delaware River. In this study, an incident similar to Athos I oil spill is considered. Three cases are prepared regarding channel closure resulting in varying degrees of impact on traffic as well as the environment. Cases A and B have a major oil spill and a cleanup effort and Case C has a medium-level environmental consequence. Through scenario

analysis the river is closed for vessel traffic for 3 days in Cases A and B, and 2 days in Case C and port performance, as well as risk performance measures are investigated.

The objective of vessel prioritization is to identify the set of products the region may immediately need and to deliver them on a timely manner. Assuming that vessel security and safety issues are handled by the USCG and other agencies, in Chapter 4, we focus on the issues regarding sequencing of vessels and decisions regarding the direction of the flow (inbound or outbound) to resume trade.

Finally, impact of vessel arrival processes on the accurate estimation of port performance as well as on the risk performance measures led us to study modeling vessel arrivals. In most simulation studies, input processes are being modeled neglecting minor correlations especially due to complexity of generating correlated processes. Even in the simulation model for Delaware River and Bay correlations on vessel arrivals are found to be negligible. On the other hand, appropriate modeling of input processes may require correlations to be taken into account for developing realistic models.

In this regard, Chapter 5 focuses on vessel arrivals at terminals. Using practice at ports and waterways, the arrival processes are characterized with one-dimensional point processes, and second order and correlation properties are investigated. The objective is modeling vessel arrivals for use in simulation studies. The analysis on vessel arrival models on queueing performance indicates the importance of variation and correlation characteristics of arrival stream on system performance. The vessel arrival data to a bauxite terminal at Port Trombetas in Brazil is used to make this demonstration. In the absence of general purpose methods for representing and generating dependent arrival processes, the study presented in this chapter provides a realistic way to model arrival processes showing special negative correlation characteristics.

# 2. SIMULATION MODELING OF THE VESSEL TRAFFIC IN DELAWARE RIVER

This chapter deals with modeling Delaware River vessel traffic. 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. A simulation model is built to be able to perform scenario and policy analyses and to support a comprehensive risk analysis of the Delaware River and Bay area. The statistics tracked are the overall port and terminal utilization, port times and terminal calls, anchorage visits and delays based on various vessel visits, categories and movements. This chapter also investigates the effects on port performance measures of deepening of the main ship channel and dredging at terminals.

The main goal behind the model development is to constitute an accurate platform to study key issues 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 validated model is needed to assess these issues. Considering the number of terminals, berth capacities and types of cargo vessels among others, simulation appears to be a sound approach. Therefore, a detailed 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. Arena 11.0 simulation software is used in the development of the model. Figure 2.1 shows an overall view of the animation layer with specific zooms at Big Stone Anchorage and Philadelphia region.



Figure 2.1 - A high level view of the Arena simulation model with specific zooms at Big Stone Beach Anchorage and Philadelphia region

The proposed model is also used to examine feasibility and the effects of port expansion projects and to perform logistics and risk analysis in the Delaware River and Bay area. 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.

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 (2008), tidal activity, lightering operation and anchorage holding activity along with

terminal operations to the extent of vessel berth holding, excluding internal terminal logistics.

Detailed historical data were obtained from the Maritime Exchange for the Delaware River and Bay 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 (actual draft of a vessel in transit), 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. The data for random components are analyzed and distributions are fitted. In addition to these, tidal activity is generated by reading (directly inputting) historical data obtained from the National Oceanic and Atmospheric Administration (NOAA) through text files into the model.

#### 2.1. 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 extend 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%). There is also tug/barge traffic carrying cargo in

and out of the port. Figure 2.2 shows the rig types and the number of vessels of a particular rig that have arrived per year.



Figure 2.2 - Annual vessel counts per rig type for years 2004 to 2008

Annually there are around 3000 vessels visiting more than 40 port facilities located in DRB. Figure 2.3 provides the total number of vessel counts between 2004 and 2008. Tug and barge activity is not included in these numbers.


Figure 2.3 - Total number of vessel calls for years 2004 to 2008

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 feet and from Delair to Trenton, NJ it is 38 feet. For vessels using CD the maximum draft limitation is 33 feet.

Along with the rules and regulations, oceanic tidal activity significantly influences the entrance of large vessels from BW. Tides recurring in almost 12-hour periods cause changes in the water level up to 6 feet 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 feet draft are affected by tide and experience extra delays in port operations.

Lightering is another activity in the system. The maximum salt-water draft in the entrance of Delaware Bay is 55 feet and Delaware River's main channel allows travel of vessels below 40 feet 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. In Figure 2.4 vessel calls are averaged annually over five years for all of the major terminals in the river.



Figure 2.4 - Average annual vessel calls in major terminals for years 2004 to 2008

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. Annually averaged vessel visits to major anchorages are given in Figure 2.5 in which tug and barge activity is not included.



Figure 2.5 - Average annual vessel visits at major anchorages for the years 2004 to 2008

# 2.2. Literature Review on Simulation Modeling of Waterways

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 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, Lagana et al. (2006) 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. (2009) 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. (2011) 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 Steenken et al. (2004).

Studies of simulation modeling of vessel traffic on waterways are not numerous but are growing. Golkar et al. (1998) developed a simulation model for the Panama Canal as a tool for scenario and policy analyses. Thiers and Janssens (1998) 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. (2003) performed traffic density analysis that 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. (2007) simulated both the freight traffic and terminal logistics for Port of Seville, Spain using the Arena software focusing on port utilization (and dredging is recommended to accommodate bigger vessels for potential growth). Smith et al. (2009)

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. (2003) developed an elementary model of the Strait of Istanbul and tested the effect of arrival intensity on waiting times. Ozbas and Or (2007) and Almaz et al. (2006) 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, vessel traffic simulations were used as an environment for further analysis of accident probabilities, risks, and economic and technical issues. Ince and Topuz (2004) 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. (2001) for Washington State Ferries in Puget Sound area and Merrick et al. (2002) for the Prince William Sound in order to perform risk assessment through integrating accident probability models. In similar studies Uluscu et al. (2009a) used a traffic simulator to test and deploy a scheduling algorithm for transit vessels in the Strait of Istanbul and Uluscu et al. (2009b) developed a dynamic risk analysis map based on an extensive vessel traffic simulation for the Strait of Istanbul. Goerlandt and Kujala (2011) also used vessel traffic simulation to evaluate ship collision probability in the open sea where environmental conditions are negligible. Somanathan et al. (2009) investigated economic viability of Northwest Passage compared to Panama Canal using simulation for vessel movements and environmental conditions. Martagan et al. (2009) 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. (2008) 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. (2003) investigated different vessel arrival methods which can be used in simulation studies and compares their effects on port efficiency. Jagerman and Altiok (2003) studied modeling of negatively correlated vessel arrivals and developed approximations for the queuing behavior. When consecutive vessels arrive at a terminal within a short time interval, the next expected vessel arrivals in a longer time interval. This is characterized with a negative correlation on interarrival times and it is a common practice for vessel arrivals at terminals. Pachakis and Kiremidjian (2003) 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. (1996) 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. The 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 was 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.

#### 2.3. Model Structure

The simulation model is developed paying attention to technical issues regarding 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.

- Randomized vessel arrivals at Breakwater (BW) and at Chesapeake and Delaware Canal (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.

Figure 2.6 illustrates the structure of the simulation model with the aforementioned components. The figure is 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.



Figure 2.6 - Model structure and vessel based flow processes

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.

## 2.3.1. Vessel Generation

Vessel types considered in this study are selected through historical data provided by the Maritime Exchange for the Delaware River and Bay. The vessel categorization in the data is adopted in this study with few vessel categories combined in order to minimize loss of information and enhance simplicity. Major vessel types visiting Delaware River and Bay area can be classified into 14 categories. These vessel types are listed below.

- Bulk (BU),
- Containership (CC),
- Chemical (CH),
- Non-flammable Product Tanker (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),
- 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 not 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. As an example, the histogram and interarrival time distribution results of the BU vessels at BW obtained from Arena's Input Analyzer are presented in Table 2.1. 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 ( $\beta$ ) 1560 and shape parameter ( $\alpha$ ) 0.909. Fitting distributions to the data was performed using Arena's Input Analyzer, and the best-fit probabilistic distributions were selected considering shape of the histograms and graphical observations, square errors achieved, goodness-of-fit tests as well as characteristics of the process.

Table 2.1 - Typical Input Analyzer distribution fit summary for interarrival tip	mes
(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			

In addition, correlations among interarrival times up to ten lags are also inspected and resulting correlogram is depicted in Figure 2.7 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 considering the complexity of generating correlated arrivals 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.



Figure 2.7 - The correlogram of interarrival times of the BU vessels at BW

For a realistic characterization of vessels and cargo loading profiles of different terminals underway drafts of vessels were analyzed and modeled using empirical distributions for each combination of terminal, vessel type and port entrance point, independently. Thus, based on the first terminal to be visited, an underway draft is assigned to each vessel generated in the model. 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 define vessel size. 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 Pachakis and Kiremidjian (2003) to estimate other vessel particulars being dependent on maximum draft. Figure 2.8 depicts 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.

These regression models are based on the data on hand, and regression types (linear or non-linear) are selected by their best match comparing adjusted R-squared values. In some cases given in Figure 2.8, selecting non-linear relationship improves the adjusted R-squared values and graphically gives better fit.



Figure 2.8 - Typical regression models for vessel particulars of maximum draft, length, beam and gross tonnage for the CC vessels

# 2.3.2. 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 2.2 each row in this matrix represents all known transitions from a terminal to other terminals, and thus adds up to 1.

Starting Torminals	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

Table 2.2 - Itinerary matrix for PG vessels

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.

# 2.3.3. 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 whose entrance and exit points are defined by virtual reference stations. 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 nodes for navigation in the river in the model. Before a vessel starts from a station, a target station is determined in the reservation procedure. 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, a 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 the entrance of the zone where the target station resides. The same procedure is used each time a vessel moves 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 \* BETA(4.28, 4.36)) distribution using historical data, as the best fit and the parameters 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, and therefore is ignored in the model.

### 2.3.4. Regulations

Navigation in the river is controlled by a number of regulations and recommendations that are clearly explained in the Coast Pilot (2008), some of which are given below:

# a. Lower River Tide Rules

- All vessels arriving with fresh water (FW)<sup>1</sup> draft in excess of 37 feet or over Panamax<sup>2</sup> size beam (106 ft) having a fresh water draft in excess of 35'-06" shall only transit during flood current<sup>3</sup>.
- 2. Vessels outbound from Paulsboro, NJ and upstream, having a fresh water draft of 37 feet and up to 40 feet should arrange to sail 2 hours after low water.

#### b. Upper Delaware River Rules

- Vessels inbound 32'-06" FW or greater up to 35'-00"FW in draft should arrive in Philadelphia harbor no later than 9 hours and 15 minutes, or earlier than 5 hours and 45 minutes from slack flood current at Cape Henlopen.
- Vessels inbound 35'-01" FW or greater up to 38'-06" FW in draft should arrive in Philadelphia harbor no later than 8 hours and 15 minutes, or earlier than 5 hours and 45 minutes from slack flood current at Cape Henlopen.

<sup>&</sup>lt;sup>1</sup> The salinity and water temperature affect water density, and hence how deeply a ship will hold in the water.

<sup>&</sup>lt;sup>2</sup> 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 feet)

<sup>&</sup>lt;sup>3</sup> Flood current is the tidal current associated with the increase in tide height.

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 hour before high water and 3 hours after high water at the dock at which it is sailing.

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

## 2.3.5. Lightering Operations

Lightering operations in Delaware River concern tankers. This is because 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 feet. In particular, 43% of the tankers have underway draft above 40 feet 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 feet 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 Andrews et al. (1996).

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 (Figure 2.9). 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:

$$L = 1.63163 * 10^{-5} * GT^{2} + 0.4544 * GT + 421.771 * D^{2} + 11551.983 * D$$
(2.1)

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



Figure 2.9 - Lightering regression plot

# **2.3.6.** 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.

#### **2.3.7.** Anchorages

There are 7 major anchorage areas in DRB considered in the model. These are listed below.

- Breakwater Anchorage (BWA) at the BW entrance (Zone 1)
- Big Stone Beach Anchorage (BSB) at the BW entrance (Zone 1)
- Reedy Point Anchorage (RP) at the CD entrance (Zone 2)
- Wilmington Anchorage (WA) (Zone 3)
- Marcus Hook Anchorage (MHA) (Zone 3)
- Mantua Creek Anchorage (MCA) (Zone 4)
- Kaighns Point Anchorage (KPA) (Zone 5)

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 2.3).

Anchorage	Draft	Length	Capacity
Kaighn's Point	$\leq$ 30 feet	$\leq$ 600 feet	7
Mantua Creek	$\leq$ 37 feet	$\leq$ 700 feet	6
Marcus Hook	$\leq$ 40 feet	-	6
Wilmington	$\leq$ 35 feet	$\leq$ 700 feet	3
Reedy Point	$\leq$ 33 feet	$\leq$ 750 feet	5
Big Stone Beach	$\leq$ 55 feet	-	-
Breakwater	$\leq$ 55 feet	-	-

Table 2.3 - Anchorage draft, length and vessel capacity limitations(Source: Coast Pilot, 2008)

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.

# 2.3.8. 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. The holding time represents a 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 all the 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.

Service processes at terminals which are referred to as the holding time in this study can be modeled in detail if and when data are available. This way, vessel particulars could be associated with the service process which may help testing different scenarios. However in this study, the data on hand do not suggest a significant relation between holding time and vessel size, particularly underway draft (Figure 2.10). 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.



Figure 2.10 - Holding time versus Underway Draft of BU vessels at Camden Marine Terminal, NJ

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, 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 2.4 shows an example of such a table for BU and TA vessels for some selected terminals.

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 + WEIB(3110, 1.37)
	5 Broadway	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 * BETA(1.44, 2.88)

Table 2.4 - Typical holding time distributions used for BU and TA vessels

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.

# 2.3.9. 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, the '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 per vessel type (total time spent in DRB),

- Terminal calls per vessel type,
- Annual anchorage visits per vessel type,
- Anchorage delays per vessel 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).

The Delaware River and Bay area sits in 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 more balanced in all three states. Thus, the model also produces state-specific output (Altiok et al., 2010). 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.

# 2.3.10. Verification & Validation

Verification is related to correct translation of a conceptual model into a simulation program. In this study, 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 submodels 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.

Validation is concerned with accurate representation of the real system through the simulation model. 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. A conclusive test of validation is to compare the model outputs to the real system data on hand (Banks et al., 2001; Law and Kelton, 2000). 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 2.5 and Figure 2.11 and Figure 2.12. Note that, the number of vessels in the system stabilizes within a couple of days when the 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.

	Actual Data 04 - 08		Simulation	
Vessel Type	Average Port Time per Vessel (min)	Average No of Vessels per Year	Average Port Time per Vessel (min) (Half Width 95% C.L)	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 (± 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 (± 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 <sup>4</sup> (TG)	4443.93	667.0	4191.7 (± 84.46)	675.5
Overall	3898.43	3789.0	3839.53 (± 39.82)	3790.5

Table 2.5 - Port times and port calls<sup>4</sup>

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 2.5 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 per cent 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.

<sup>&</sup>lt;sup>4</sup> Actual Tug Boat data are based on 2004 only.



Figure 2.11 - Selected terminal utilizations per berth

Terminal berth utilizations shown in Figure 2.11 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 per cent difference while rest of the terminals lie around 2 per cent difference from the actual utilizations. 95% confidence intervals are also obtained for terminal utilizations.



Figure 2.12 - 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 Figure 2.12, annual visits and average delays in all anchorages are 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.

According to Law (2009) the accuracy required from a model depends on its intended use and the utility function of the decision-maker since the most valid model is not necessarily the most cost effective. 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.

### 2.4. Analysis on Impact of Deepening on Navigational Issues

Delaware 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 feet 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 feet below Mean Low Water (MLW) and provision of a two-space anchorage to a depth of 45 feet at Marcus Hook.

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 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 (USACE, 2002).

Investigation of impacts of deepening/dredging on various port performance measures is scarce in literature. Grigalunas et al. (2005) 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. There are also governmental economic analysis update reports prepared by the U.S. Army Corps of Engineers (USACE, 2004; USACE, 2008; USACE 2011), and the U.S. Government Accountability Office's reports recommending a comprehensive reanalysis (GAO, 2002), and recommending updated assessments on relevant market and industry trends (GAO, 2010). On the other hand, there are environmental and ecological reports by several governmental agencies and studies in literature, which are beyond scope of this study. Apart from these work, to the best of our knowledge no further directly related efficiency analysis to deepening/dredging is noticed in academic literature. Thus, the analysis presented here underlines the need for such academic work during dredge/deepening planning processes in any port or waterway system.

The motivation behind this section 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. The simulation model developed is modified 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 objectives of this section 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 feet,
- Change vessel configuration and bring larger vessels

Relevant scenarios are described in the scenario analysis section below.

## 2.4.1. Scenario Assumptions

The scenario analysis presented in this section 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 U.S. Army Corp of Engineers (USACE, 2002) are used.

The scenarios presented in this section 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.

## 2.4.1.1. Trade Growth

Future trade forecast for Delaware River port system is investigated in the deepening analysis report of the USACE (2002). 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 2.6, thus future vessel arrival patterns for the next 30 years are estimated annually and incorporated for almost all vessel types in the model. The vessel type descriptions are given in Section 2.3.1 for the abbreviations used in the table. Note that the rates given in the table are annual and compounded throughout 30 years.

Table 2.6 - Annual percentage increase in arrival rates by vessel type

(Source:	USACE, 2002)
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	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.

# **2.4.1.2.** 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 feet from the Delaware Bay entrance to the Philadelphia Harbor, PA and to Beckett Street Terminal, Camden, NJ and will provide 45 feet depth at the MHA. Terminals in this region might benefit from the deepening project by dredging nearby their berths. Based on the USACE (2002) report, berth deepening data for dredge designated terminals given in Table 2.7 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 based on the holding time and total cargo on the vessel is calculated in the model. This ratio is used on the tonnage difference being carried to the terminal, and holding time is increased.

If deepening of the main channel occurs, some regulations controlling the navigation in the river will have to be revised. Since deepening concerns the river up to Philadelphia region, tide regulations regarding the Lower River are relaxed by 5 feet in the model. Therefore, inbound tidal delays in BWA and outbound tidal delays especially in the MHA would be reduced.

In the deepening 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.

Table 2.7 - Terminal berth dredging plans

Terminal/Company	Berth	Depth (ft.)
Fort Mifflin (Sun)	А	$38 \rightarrow 45$
Fon Mijjith (Sun)	В	$37 \rightarrow 45$
	3C	$40 \rightarrow 45$
Margus Hook (Sun)	3A	remains 39
Marcus Hook (Sun)	2A	remains 37
	3B	remains 17
Paulshoro (Valaro)	Berth # 1 (Tanker Berth)	$40 \rightarrow 45$
T duisboro (valero)	Berth # 2	remains 30
	Berth # 1	remains 34
Eagle Point (Sun)	Berth # 2	$40 \rightarrow 45$
	Berth # 3	$40 \rightarrow 45$
Conoco Philips	Berth # 1	$38 \rightarrow 45$
	Berth # 1	$\rightarrow 45$
Valero/Premcor Delaware City	Berth # 2	$\rightarrow 45$
	Berth # 3	$\rightarrow 45$
Wilmington Oil Pier	Liquid Bulk Berth	$38 \rightarrow 45$
PackerAvenue	5 front berths	$40 \rightarrow 45$
	the bottom berth	remains 40
	Berth # 4	$40 \rightarrow 45$
Beckett Street	Berth # 3	remains 35
	Berth # 2	remains 30
Wilmington Port	All berths in Christina River	$38 \rightarrow 42$

(Source: U	SACE,	2002)
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#### **2.4.1.3.** Shift to A Fleet of Larger Vessels

Under the deepening project 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 (2002) 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 feet and reducing the total number of vessels 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 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 to 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  $S_k = \sum_{i=1}^{N_k} GT_{i,k}$  // 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 feet

Step 7: Set  $GT_{i,k}^+ \leftarrow f_k(d_i^+)$  // set increased tonnage for vessel *i* arriving at terminal *k* 

Step 8: Let  $R_k^* = \frac{\sum_{i=1}^{N_k} GT_{i,k}^+}{S_k}$  // 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 feet, 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.

## 2.4.2. 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 section and aggregate (non-state based) results are presented accordingly.

The number of replications is decided based on the tests as depicted in Figure 2.13 where the average port time for tankers stabilizes after around 30 replications, nevertheless 100 replications is selected for consistency. Furthermore, Figure 2.13 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.



Figure 2.13 - 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

Port times, port calls, anchorage visits and anchorage delays are reported for the first year and for the 30<sup>th</sup> 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 DRB and constitute a basis for the scenario comparisons. The 30<sup>th</sup> year results are given due to increase of vessel arrivals as a result of simulated trade growth, thus these results help us to understand likely future effects of deepening and 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 1,000 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 the same in all scenarios.

The results of the scenarios with their 95% confidence intervals based on 100 replications are given in Table 2.8 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.

Scenarios - First Year Results Outputs		Vessel Types					
		BU	CC	GC	TA		
Scenario B	Average Port Time per Vessel (hrs)	$93.17\pm0.99$	$32.72\pm0.31$	$63.51\pm0.66$	$82.75\pm0.95$		
Growth	Average No of Vessels per Year	$419\pm4$	$465 \pm 4$	$260 \pm 3$	$917 \pm 6$		
	Average Port Time / Kton (hrs)	$3.75\pm0.04$	$1.36\pm0.01$	$5.12\pm0.06$	$1.57\pm0.02$		
Scenario C	Average Port Time per Vessel (hrs)	$92.43 \pm 1.02$	$32.14\pm0.25$	$62.63\pm0.72$	$71.10\pm0.48$		
Growth + Deepen	Average No of Vessels per Year	$416\pm5$	$463 \pm 3$	$262 \pm 3$	$919 \pm 6$		
	Average Port Time / Kton (hrs)	$3.72\pm0.04$	$1.34\pm0.01$	$5.05\pm0.06$	$1.35\pm0.01$		
Scenario D	Average Port Time per Vessel (hrs)	$103.97 \pm 1.45$	$37.01\pm0.36$	$69.07 \pm 1.00$	$98.48 \pm 1.34$		
Growth + Deepen + Larger Vessels	Average No of Vessels per Year	$383 \pm 4$	$378 \pm 3$	$243 \pm 3$	$772 \pm 4$		
	Average Port Time / Kton (hrs)	$4.04\pm0.06$	$1.31\pm0.01$	$5.18\pm0.07$	$1.62\pm0.02$		

Table 2.8 - First year port results with 95% confidence intervals

Table 2.9 shows the results for the 30<sup>th</sup> 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.

Scenarios - 30th Year Results	Outputs	Vessel Types				
		BU	CC	GC	TA	
Scenario B	Average Port Time per Vessel (hrs)	$104.58\pm1.43$	$33.72\pm0.22$	$68.97 \pm 0.82$	$91.42 \pm 1.67$	
Growth	Average No of Vessels per Year	$610 \pm 5$	$1049 \pm 5$	$378 \pm 3$	$1031 \pm 6$	
	Average Port Time / Kton (hrs)	$4.21\pm0.06$	$1.41\pm0.01$	$5.58\pm0.07$	$1.73\pm0.03$	
Scenario C	Average Port Time per Vessel (hrs)	$103.12\pm1.57$	$33.40\pm0.25$	$69.82\pm0.86$	$72.36\pm0.48$	
Growth + Deepen	Average No of Vessels per Year	$612 \pm 5$	$1051 \pm 6$	$379 \pm 4$	$1027\pm 6$	
	Average Port Time / Kton (hrs)	$4.15\pm0.06$	$1.39\pm0.01$	$5.60\pm0.07$	$1.37\pm0.01$	
Scenario D	Average Port Time per Vessel (hrs)	$124.47 \pm 2.63$	$38.74 \pm 0.28$	$79.45 \pm 1.26$	$111.03\pm2.48$	
Growth + Deepen + Larger Vessels	Average No of Vessels per Year	$559 \pm 5$	$854 \pm 5$	$353 \pm 4$	$878\pm5$	
	Average Port Time / Kton (hrs)	$4.83\pm0.10$	$1.37\pm0.01$	$5.96\pm0.10$	$1.81\pm0.04$	

Table 2.9 - 30<sup>th</sup> year port results with 95% confidence intervals

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 Kaighns Point) are aggregated in the results as four anchorages.

First year results of the scenarios are given in Table 2.10. 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.

Scenarios - First Year Results		Vessel Types				
			BU	CC	GC	TA
Scenario B	BWA	Average Delay per Vessel (hrs)	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 (hrs)	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 (hrs)	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 (hrs)	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 (hrs)	14.12	8.17	7.22	12.10
Growth + Deepen + Larger Vessels		Average No of Visits per Year	49	6	10	78
4 Anch		Average Delay per Vessel (hrs)	54.22	9.67	33.85	17.77
		Average No of Visits per Year	96	16	42	321

Table 2.10 - First year anchorage results (delays and visits)

Anchorage results as they are observed in the 30<sup>th</sup> year are shown in Table 2.11. 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 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.

Scenarios - 30th Year Results		Vessel Types				
			BU	CC	GC	TA
Scenario B	BWA	Average Delay per Vessel (hrs)	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 (hrs)	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 (hrs)	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 (hrs)	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 (hrs)	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 (hrs)	95.56	17.69	63.34	18.41
	-	Average No of Visits per Year	178	56	83	338

Table 2.11 - 30<sup>th</sup> year anchorage results (delays and visits)

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 2.12 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.

Scenarios	Outputs	First Year	30th Year
Scenario B	Average Delay per Vessel (hrs)	59.77	77.80
Growth	Average No of Visits per Year	396	443
Scenario C	Average Delay per Vessel (hrs)	42.80	44.29
Growth + Deepen	Average No of Visits per Year	237	263
Scenario D	Average Delay per Vessel (hrs)	66.79	95.59
Growth + Deepen + Larger Vessels	Average No of Visits per Year	285	326

Table 2.12 - Big Stone Beach Anchorage results for Tankers

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. Figure 2.14 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.



Figure 2.14 - Port Occupancy in the river observed in the 30-year planning horizon

#### **2.4.3. Remarks on Results of Deepening Analysis on Navigational Issues**

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 for the planning horizon. 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 no 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.

## 2.5. Conclusion on Simulation Modeling and Deepening Analysis

In this chapter, simulation modeling of vessel traffic in Delaware River and Bay is presented with an analysis on the impact of deepening on the navigational issues. The chapter elaborates on the simulation model built, develops scenarios to perform an analysis on the effects of deepening and discusses the results of the scenarios on navigational benefits. The results present 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 analysis does not evaluate potential reduction in operating costs due to decreased 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 may have a positive impact.

Another product of this study is the simulation model itself, developed for Delaware River and Bay as a decision support tool. The model produces an accurate representation of the main channel traffic for all vessel and cargo types, and terminals. The model and its findings were already put into use in understanding the impact of the planned vessel stream for the Paulsboro terminal of the South Jersey Port Corporation on the overall port performance in Delaware River. With modification, 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 in the Delaware and Bay area.

In regard to a future 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 the 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 chapter, 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. In this respect, effects and modeling of negatively correlated vessel arrivals are investigated in Chapter 5.

# 3. RISK ANALYSIS OF THE VESSEL TRAFFIC IN DELAWARE RIVER

This chapter deals with comprehensive risk analysis of the vessel traffic in Delaware River and Bay area. The purpose is to develop a risk model to incorporate into the simulation model presented in Chapter 2 in order to study the safety risks due to the vessel traffic in the river.

Assessment and mitigation of current risks inherent in the Delaware River and Bay vessel traffic require the development of a post-incident recovery strategy. A model-based risk analysis in the DRB area is carried out to identify which zones of the river have higher risks, what the magnitudes are and what the possible mitigation measures may be. First, a probabilistic risk model is developed considering all possible accidents as suggested by the historical data in DRB. Expert opinion elicitation process helps computing the unknown accident and consequence probabilities for various situations. Next, the risk model is incorporated into a simulation model to be able to evaluate risks and to produce a risk profile of the entire river. Figure 3.1 shows the main components of this approach. A scenario analysis is performed in the end in order to study the behavior of accident risks over time and geographic domain. The approach can be implemented to evaluate risks in other systems of interest as well.



Figure 3.1 - Risk assessment approach

In the history of Delaware River, there have been several accidents with serious consequences and major impact on its operation. The Grand Eagle accident in 1985 and Presidente Rivera in 1989 caused 306,000 gallons and 435,000 gallons of oil spills respectively. Lately, in November 2004, another major oil spill occurred when the 750-foot tanker M/V Athos I struck a submerged anchor in Paulsboro. The resulting breach in the ship's hull spilled approximately 265,000 gallons of crude oil into the river and the entire channel was closed to traffic for three days (University of Delaware Sea Grant Program, 2004). Apart from these, there have been many minor and major accidents

causing damage to property and harm to human life. In July 2010, collision of the tugboat Carribean Sea and the passenger vehicle DUCKW34 caused fatal and minor injuries of passengers, and has drawn significant public attention (National Transportation Safety Board, 2011).

The long-term demand for energy products such as petroleum and natural gas translate into significant increases in projected numbers of crude oil, LPG and, potentially LNG carriers and corresponding port calls required to meet future demand. Lloyd's Register World Fleet Statistics (2010) shows the world fleet exceeded 100,000 ships with around 17% increase in number and 54% increase in gross tonnage since past 10 years. Besides, the total number of LNG carriers reached 357 as of 2012 and expected to reach 436 by 2016 according to LNGC Builders (2012). In particular, the DRB is expected to have increased vessel traffic, or traffic involving larger vessels due to deepening, giving rise to concerns for port performance and risk. Also, the SAFE Port Act of 2006 (PL 109-711) requires Area Maritime Security Plans to include preparedness, response and recovery plans to ensure that commerce is rapidly restored in U.S. ports following a transportation incident. All of these motivated the need to study the risks inherent in DRB vessel traffic to better develop post incident recovery strategies.

In this chapter, the approach to evaluate risks in DRB is a hybrid one in the sense that it involves both a mathematical risk model and a simulation model developed. Although traffic patterns change over time in a complex manner, simulation models may help understanding dynamic nature of relations through changing system parameters and/or implementing new rules, testing scenarios and new policies. This way, evolution of risk behavior can also be investigated. These two models work in lock step in such a way that the simulation model generates all possible knowable situations and passes them on to the mathematical model for risk evaluations. By repeating the risk evaluation process at every short time interval, it is possible to generate the zone-based risk profile of the entire river. In this regard, this chapter deals with a framework for maritime risk assessment, provides results of risk assessment for Delaware River and Bay, and tests scenarios to evaluate impacts of trade growth, deepening DRMC and bringing larger vessels as well as possible risk mitigation policies.

## **3.1.** Risk Analysis Concepts

Risk analysis is one of the mostly visited and diverse areas in literature and the concept of risk is closely related to topic of uncertainty. In Lowrence (1976), risk is defined as a measure of the probability and severity of adverse effects. In accordance with this definition, risk has been explained using terms such as situation, likelihood and consequences many times in literature (Kaplan and Garrick, 1981; Kaplan, 1997; Aven, 2008; Haimes, 2009). A situation represents circumstances which can lead to an undesirable consequence. Likelihood is the frequency or the degree of certainty of this situation to happen. Thus, starting with these arguments, risk can be expressed as the expected value of the undesirable consequence in a situation. That is,

$$R_s = p_s \times C_s \tag{3.1}$$

where s represents a situation,  $R_s$  is the risk of the situation,  $p_s$  is the probability of occurrence of the situation and  $C_s$  is the consequence of the situation in case it occurs.

A situation can be described using an array of variables which also makes the risk a function of this set of variables. Thus, this perspective in risk analysis can be summarized as the study of situations and possible consequences with relative probabilities. There have been many definitions used such as *probabilistic risk analysis* (PRA), *quantitative risk analysis* (QRA) or *probabilistic safety analysis* (PSA) to characterize the approach when probability is used to model uncertainty (Bedford and Cooke, 2001).

According to a widely accepted definition by Society for Risk Analysis (SRA), risk analysis is a thorough examination including risk assessment, risk evaluation, and risk management, performed to understand the nature of undesirable, negative consequences to human life, property, or the environment. In this regard, the entire risk assessment and management process is described in Haimes (2009) with the following five steps:

- 1. Risk identification
- 2. Risk modeling, quantification, and measurement
- 3. Risk evaluation
- 4. Risk acceptance and avoidance
- 5. Risk management

Kaplan and Garrick (1981) relate the above first three steps with the risk assessment questions below:

- 1. What can go wrong?
- 2. What is the likelihood that it would go wrong?
- 3. What are the consequences?

The other two steps, risk acceptance and avoidance, and risk management, are characterized in Haimes (1991) with the questions below:

- 1. What can be done, and what choices are available?
- 2. What are their associated trade-offs in terms of costs, benefits and risks?
- 3. What are the impacts of current decisions on future choices?

Risk analysis has been evolved through its use in many industries such as the aerospace sector, the nuclear sector and the chemical process sector since 1970s (Bedford and Cooke, 2001). It has also become important in maritime transportation after serious accidents, and the National Research Council identified maritime risk analysis as an important problem domain (Transportation Research Board, 2000).

In this research, the focus is on developing a methodology for quantification of risks for the risk assessment of vessels traffic in Delaware River and experimenting with possible options to assist risk management strategies.

## **3.2.** Literature Review on Maritime Risk Analysis

Risk analysis grew from safety analysis and focuses on uncertainty and its presence in design of complex systems. Risk analysis in maritime domain has taken several

directions. While some studies are focusing on safety of individual vessels and structural design using the tools of reliability engineering (Wang, 2001), others deal with accident probability estimation, consequence analysis, and/or estimation of risks in collective systems. Methods used in these studies vary from event/fault tree analysis to Bayesian network approaches, statistical analysis of historical data to expert judgment elicitation, predictive modeling approaches such as geometrical probability estimation to simulation modeling. In this review, papers that have major impact on maritime risk analysis and are relevant to this study are considered.

Soares and Teixeria (2001) summarized the approaches used in risk assessment for maritime transportation. While the early applications were mostly on risks of individual vessels, more recent work has focused on decision making such as regulations to govern international maritime transportation. Studies based on accident statistics mainly contributed to the literature providing the evolution of levels of safety in maritime transportation of failures in different types of ships and demonstration of the overall current picture. The risk of failure in individual ships has also been studied using various approaches. Collision, grounding and sinking are mainly the focus in these studies. Reliability based methods have been used in mostly structural design problems to answer questions such as ultimate failure of the structure and different modes of structure failure. Formalized Safety Approach (FSA) is a term devised by the International Maritime Organization (IMO) for studies that use formalized analysis and quantification of risks. FSA is mostly concerned with organizational, managerial, operational, human and hardware aspects of the collective system. As an example, Trbojevic and Carr (2000)

employed the stepwise approach of FSA for hazard identification and qualitative risk assessment.

Fowler and Sorgard (2000) worked on maritime transportation risk under the project "Safety of Shipping in Coastal Waters" (SAFECO). In their study, Marine Accident Risk Calculation System (MARC) was used which was based on causes of important accidents found in historical data. They used Vessel Traffic System (VTS) database and environment data for accident frequency calculations, fault and event tree analysis, expert judgment and physical models to calculate failure probabilities, accident frequencies and possible consequences to come up with a risk assessment.

In recent years, simulation has been a powerful tool to assist risk analysis (Hara and Nakamura, 1995; Bruzzone et al., 2000; Or and Kahraman, 2002). Merrick et al. discuss assessment of risks, which became a major concern after the grounding of Exxon Valdez, due to oil tankers in the Prince William Sound in complementary papers (Harrald et al., 1998; Merrick et al., 2000; Merrick et al., 2002). Their work is a prominent example of combining systems simulation and expert judgment elicitation with probabilistic risk assessment (PRA) techniques. In their study, the consequence of interest is oil spills due to accidents. They discuss the details of their risk assessment approach and provide results for accident frequencies, oil outflow rates and impacts of risk mitigation policies. Similarly, van Dorp et al. (2001) used simulation to obtain collision probabilities based on historical data and expert judgments for the risk evaluation of Washington State Ferries. Risk reduction policies are tested to develop risk management recommendations.

They define mitigation policies as risk interventions and provide a model to evaluate their impacts compared to the baseline level of risk. Uluscu et al. (2009b) extended the approach in these studies (Merrick et al., 2000; Merrick et al., 2002; van Dorp et al., 2001) to investigate safety risks on the transit vessel traffic in the Strait of Istanbul. They analyzed the transit vessel traffic system in the Strait and developed a simulation model to mimic maritime operations and environmental conditions. The risk model employs subject-matter expert opinion in identifying probabilities regarding instigators, accidents and consequences.

Uncertainty is an important aspect of risk discussed in the different phases of risk analysis studies (Parry, 1996; Winkler, 1996; Nilsen and Aven, 2003). Uncertainty is experienced in modeling, probability assessment and even in sensitivity analysis phases. In order to examine uncertainty, Merrick et al. (2005a) worked on a Bayesian simulation technique to be used in the maritime risk assessment. Using a Bayesian approach for input and output data modeling, it is claimed that epistemic uncertainty due to lack of knowledge about the system as well as aleatory uncertainty due randomness of the system itself could be treated. They implemented this methodology as an example to their earlier study of expansion of San Francisco Bay ferries. In another study, Merrick et al. (2005b) developed a Bayesian multivariate regression methodology to be applied to expert judgment data elicited to evaluate the effect of factors on situations creating accident risks. Finally, in Merrick and van Dorp (2006), these two methodologies were combined through two case studies in order to perform a full scale maritime risk assessment. Lately, van Dorp and Merrick (2011) summarized the evolution of their risk analysis methodology they have been working for more than a decade and provided new enhancements in their simulation modeling and accident frequency estimations.

In order to support decision making process of the U.S. Coast Guard, Merrick and Harrald (2007) used multi-attribute decision analysis techniques, particularly the Analytical Hierarchy Process (AHP), to develop ports and waterways safety assessment model (PAWSA). They conducted group decision sessions in 26 U.S. ports and waterways to reveal vulnerability issues through prioritizing attributes of a port that affect safety. They also evaluated effectiveness of alternative technologies to solve problems in the port or waterway under consideration. However, PAWSA model does not have a dynamic nature since the process is solely dependent on the qualitative information provided by experts.

Other studies combined historical data and expert judgment to evaluate risks in the collective systems. Vanem et al. (2008) considers the risk of LNG carriers to human lives, particularly to ship crew, passengers and third parties. They used event trees, historical data and expert judgment to quantify accident probabilities and associated risks, and evaluated risk acceptance. As an improvement to event/fault trees, Trucco et al. (2008) used Bayesian belief networks to identify factors effecting maritime accidents and estimated probabilities based on expert judgments.

Yip (2008) performed a statistical analysis on historical accident data for the Hong Kong port and pointed out that, considering hourly distribution of accidents, potential issues in

the the traffic system has greater impact on risks than individual vessels. Besides, it is observed that vessel type, port of registration and accident type have significant impacts on the number of injuries and fatalities, and concluded that a comprehensive database of accidents is essential for the improvement of port traffic control. Kujala et al. (2009) also did statistical accident analysis in the Gulf of Finland and used theoretical models to obtain collision probabilities. They recommend using simulation to mimic realistic ship movements and to overcome distributional assumptions in their theoretical collision model. Later, Goerlandt and Kujala (2011) used vessel traffic simulation to evaluate ship collision probability in the open sea, yet they did not consider environmental effects.

In addition to many studies described above, review articles help better understanding of the current state in maritime risk analysis and provide insight for future studies. Recently, Pedersen (2010) reviewed methods used in analyzing collisions and groundings and discusses tools to obtain probabilities and consequences. Li et al. (2011) provided an extensive review of quantitative risk assessment models in literature. They expect research focusing on modeling and quantification of human error, being a major cause of accidents, and underline the necessity of extensive data collection in maritime domain. Greenberg (2009) summarized fundamentals of risk analysis in the maritime domain and especially in the port security context and provided suggestions to overcome challenges in the area.

Risk analysis has various interesting and widely discussed concepts and approaches in it. Due to the possible and growing application areas, risk analysis can be a useful decision support tool for various industries as well as for maritime industry. Besides, as the risk analysis applications increase the framework and methodologies developed can be applicable to other domains.

## **3.3.** Risk Assessment Framework in DRB

In this section, the risk assessment framework in the DRB area is established by first looking into the causal chain of events from instigator occurrences to accidents and finally consequences. Accidents typically occur as a result of a chain of events rather than being independent single events (Garrick, 1984). The initial step of the risk assessment process is to identify reasons and outcomes of accidents. This process can be quite detailed and yet due to data requirements, when a mathematical model is involved, the chain defining the risk framework should be limited to triggering events, major accident types and significant consequences. Similar events and situations are also used in many maritime risk assessment studies (Soares and Teixeria, 2001; Trbojevic and Carr, 2000; Fowler and Sorgard, 2000; Bruzzone et al., 2000; Harrald et al., 1998; Merrick et al., 2000; Merrick et al., 2002; van Dorp et al., 2001; Ulusçu et al., 2009b). In view of this, Figure 3.2 shows the general risk framework for the DRB area.



Figure 3.2 - Risk assessment framework for DRB

Instigators can be defined as major triggering events which may be followed by an accident. Thus, it is assumed that an accident cannot take place just by itself unless an instigator occurs. Based on the USCG accident data for DRB, instigators are identified as shown below:

- Human Error (HE) may include "not following the policies or best practice", "communication breakdown", "inadequate situational awareness" and etc.
- Propulsion Failure (PF) may include "engine breakdown", "contaminated fuel problem", "propeller problem" and etc.
- 3. Steering Failure (SF) may include "hydraulic system failure", "rudder problem" and etc.
- 4. Electrical / Electronic Failure (EF) may include "generator failure", "computer software problems", "navigation and communication system failure" and etc.

5. Other Systems Failure (OSF) may include "hull structure problems", "cargo and cargo control systems failure" and etc.

Figure 3.3 presents the number and relative percentage of the aforementioned instigators happened in DRB through 17 years beginning 1992. The data are extracted and categorized from the DRB accident data provided by the USCG headquarters in Washington D.C.



Figure 3.3 - Number and share of instigators in the historical accident data from 1992 to 2008 (Source: USCG)

Accidents are the unexpected and undesirable events resulting in some sort of damage.

DRB accident data suggests the following categorization of accidents:

- 1. Collision (C) the structural impact between two moving vessels.
- 2. Allision (A) the impact of a vessel with a stationary object.

- 3. Grounding (G) the impact of a vessel on the seabed.
- 4. Fire / Explosion (F/E)
- 5. Sinking / Capsizing / Flooding (S/C/F) descend beneath the sea level / overturn / overflowing of water on the vessel.
- 6. Oil spill (OS) petroleum leak from a vessel

These types of accidents happened in Delaware River throughout 17 years as Figure 3.4 illustrates.



Figure 3.4 - Number and share of accidents in the historical accident data from 1992 to 2008 (Source: USCG)

Consequences typically are damages or harm to physical assets or humans as a result of an accident. Based on DRB accident data consequences are grouped into the following three categories:

- 1. Human Casualty (HC) may include death, permanent disabling injury, and minor injury
- 2. Environmental Damage (EnvD) may include impact to wild life and habitat, loss of commercial and recreational use, danger to human life, oil spill and etc.
- 3. Property Damage (ProD) may include damage to the vessel or other properties involved in the accident.

Clearly, these categories cover a wide range of consequences. Hence these groups are each further classified into subcategories such as low and high; where high for human casualty may mean death, permanent disabling injury cases and low may mean minor injury. High impact to wildlife and habitat, loss of commercial and recreational use, danger to human life, moderate to large amounts of oil spills and etc. are considered to be high environmental damages. Damage to a vessel or other properties involved in an accident costing less than 10,000 dollars are typically considered as a low consequence. Accordingly, the historical data provides the categories of consequences as shown in Figure 3.5.



Figure 3.5 - Number and share of consequences in the historical accident data from 1992 to 2008 (Source: USCG)

As Figure 3.2 shows there exists a sequential causal relationship among instigators, accidents and consequences such that instigators may lead to accidents and accidents cause consequences. Each instigator leads to specific types of accidents with a probability as given in Table 3.1. For instance, collision occurred in 12.69% of all the human-error related incidents. The probabilities in Table 3.1 to Table 3.3 are calculated based on the 17 years of accident data provided by USCG. These numbers are used later in the calibration process.

		Accidents					
					Eino /	Sinking /	
	P(Accident   Instigator)	Collision Alli	Allision	Grounding	File /	Capsizing	Oil Spill
					Explosion	/ Flooding	
s	Human Error	0.1269	0.2463	0.3993	0.0560	0.0299	0.0336
tor	Propulsion Failure	0.0349	0.0349	0.0291	0.0174	0.0001	0.0058
iga	Steering Failure	0.0566	0.0377	0.0943	0.0002	0.0002	0.0755
nst	Electrical / Electronic Failure	0.0003	0.0256	0.0513	0.0513	0.0003	0.0003
Ι	Other Systems Failure	0.0074	0.0662	0.0662	0.0735	0.1029	0.2941

Table 3.1 - Probability of accident occurrence given an instigator based on the historical accident data of 1992 to 2008 (Source: USCG)

Table 3.1 shows an instigator may lead to an accident with the associated probability or there may be no accident. Using this relationship, a conditional probability expression can be written as in Equation 3.2 where  $A_{j,v} = \{0, 1\}$  is the indicator variable for accident type *j* on a vessel *v*, and equals 1 if accident happens or equals 0 if accident does not happen, and likewise  $I_{i,v} = \{0, 1\}$  is the indicator variable for instigator type *i* on a vessel *v*. In the following equations, the notation of  $A_{j,v}$  indicates  $A_{j,v} = 1$  for simplicity.

$$\Pr(A_{j,\nu}, I_{i,\nu}) = \Pr(A_{j,\nu} | I_{i,\nu}) \times \Pr(I_{i,\nu})$$
(3.2)

In order to eliminate the interaction terms and to express the overall probability of accident, the set of instigators need to be assumed mutually exclusive and collectively exhaustive. Then, the probability of an accident type *j* on a vessel *v* can be estimated using Equation 3.3 where  $Pr(A_{j,v} = 1 | I_{i,v} = 0)$  is omitted since it is 0.

$$\Pr(A_{j,\nu}) = \sum_{i} \Pr(A_{j,\nu} | I_{i,\nu}) \times \Pr(I_{i,\nu})$$
(3.3)

Since the relationship chain begins with an instigator, the instigator occurrence probability needs to be obtained as well. Table 3.2 shows the historical data on the probability of occurrence of each instigator for any type of vessel and it is assumed that these probabilities can be used as an estimator for  $Pr(I_{i,v})$ .

InstigatorsP(Instigator)Human Error0.0054Propulsion Failure0.0034Steering Failure0.0011Electrical / Electronic Failure0.0008

0.0027

Other Systems Failure

Table 3.2 - Probability of instigator occurrence based on 50,000 vessels in the historical accident data of 1992 to 2008 (Source: USCG)

Numbers in Table 3.3 show the probabilities of consequences to happen as a result of accidents. An accident may cause multiple consequences and consequences are assumed independent of each other. For instance, human casualty occurred in 5.41% of all collisions (in single as well as multiple consequence occurrences). Note that, row sums in the table may exceed unity due to the inclusion of joint consequence probabilities in each of the marginal consequence probabilities.
		Consequences				
		Human	Environmental	Property		
	P(Consequence   Accident)	Casualty	Damage	Damage		
	Collision	0.0541	0.1081	0.9730		
lts	Allision	0.0482	0.0843	0.9759		
den	Grounding	0.0394	0.0630	0.9685		
cci	Fire / Explosion	0.3571	0.1071	1		
V	Sinking / Capsizing / Flooding	0.0455	0.5455	0.9545		
	Oil Spill	0.0556	1	0.2778		

Table 3.3 - Probability of consequence occurrence in an accident based on the historicalaccident data of 1992 to 2008 (Source: USCG)

Again using the relationship given in Table 3.3 a conditional probability expression can be written as in Equation 3.4 where  $C_{k,v} = \{0, 1\}$  is the indicator variable for consequence type *k* on a vessel *v* and equals 1 if there is a significant consequence or equals 0 if there is no significant consequence.

$$\Pr(C_{k,\nu}, A_{j,\nu}) = \Pr(C_{k,\nu} | A_{j,\nu}) \times \Pr(A_{j,\nu})$$
(3.4)

Assuming that the set of accidents are mutually exclusive and collectively exhaustive, the probability of a consequence type k on a vessel v can be estimated using Equation 3.5 where  $Pr(C_{k,v} = 1 | A_{i,v} = 0)$  is omitted since it is 0.

$$\operatorname{Pr}(C_{k,\nu}) = \sum_{j} \operatorname{Pr}(C_{k,\nu} \mid A_{j,\nu}) \times \operatorname{Pr}(A_{j,\nu})$$
(3.5)

If the random variable  $Q_{k,j,v}$  indicates the severity (impact) of consequence k when a consequence occurs as a result of accident j on a vessel v then the expected impact of a

consequence can be expressed with Equation 3.6. Notice that  $Q_{k,j,v} = 0$  when there is no accident or no consequence.

$$E[Q_{k,j,\nu} | C_{k,\nu}, A_{j,\nu}] = \sum_{Q_{k,j,\nu}} Q_{k,j,\nu} \times \Pr(Q_{k,j,\nu} | C_{k,\nu}, A_{j,\nu}) \quad \text{and}$$
$$E[Q_{k,\nu}] = \sum_{A_{j,\nu}} E[Q_{k,j,\nu} | C_{k,\nu}, A_{j,\nu}] \times \Pr(C_{k,\nu} | A_{j,\nu}) \times \Pr(A_{j,\nu}) \quad (3.6)$$

Eliminating the zero terms in the Equation 3.6, assuming the consequences are independent of each other and using the definition of risk as expected value of the undesirable consequences then  $R_v$  representing the risk on a vessel *v* can be expressed with Equation 3.7.

$$R_{\nu} = \sum_{k} E[Q_{k,\nu}] = \sum_{k} \sum_{j} E[Q_{k,j,\nu} | C_{k,\nu}, A_{j,\nu}] \times \Pr(C_{k,\nu} | A_{j,\nu}) \times \Pr(A_{j,\nu}) \text{ or}$$

$$R_{\nu} = \sum_{k} \sum_{j} \sum_{i} E[Q_{k,j,\nu} | C_{k,\nu}, A_{j,\nu}] \times \Pr(C_{k,\nu} | A_{j,\nu}) \times \Pr(A_{j,\nu} | I_{i,\nu}) \times \Pr(I_{i,\nu})$$
(3.7)

Beside these causal relationships, there are other factors that may increase or decrease the chances of instigators, accidents, and consequences to take place (Merrick et al., 2000; Merrick et al., 2002; van Dorp et al. 2001). They are referred to as situational attributes. For example, the probability of collision may increase due to loss of visibility or due to seasonal conditions. Generally these attributes are classified into two groups: vessel attributes and environmental attributes as shown in Figure 3.6.



Figure 3.6 - Situational attributes affecting accident occurrences and the consequences

Each situational attribute has its finite number of states. For example, the environmental attribute season describe one of the four natural divisions of the year, spring, summer, fall or winter. This way, specific meteorological and climatic conditions of a situation is represented. The states of all variables are given in Table 3.4 below. Note that, there are a total of 25,920 different possible situations for the selected set of 8 situational attributes considering the possible number of states for each attribute. This immediately justifies the need to develop a model to keep track of the dynamics of the causal chain introduced above and to evaluate the resulting risks.

Variable	Situational Attribute	Possible Values	States		
V	Time of Day	2	Day,		
Λ]	Time of Day	2	Night		
X.	Tide	2	High,		
<b>M</b> 2	1 100	-	Low		
			Docked,		
$X_{3}$	Vessel Status	3	Underway,		
			Anchored		
			General Cargo < 150m,		
			General Cargo $\geq$ 150m,		
			Tugboat / Barge,		
			Passenger $\geq$ 100GT,		
v	Vascal Class	10	Petroleum Tanker < 200m,		
$\Lambda_4$	VESSEICLASS	10	Petroleum Tanker ≥ 200m		
			Chemical Tanker < 150m,		
			Chemical Tanker $\geq$ 150m,		
			LNG / LPG,		
			Lightering Barge		
		6	Delaware Bay,		
			CD Canal Region,		
v	Zone		Wilmington Region,		
<b>A</b> 5			Paulsboro Region,		
			Philadelphia Region,		
			Upper Delaware River		
	No. of Vascala		0 or 1 vessel,		
$X_6$	within 5NM	3	2 to 3 vessels,		
			more than 3 vessels		
	No. of Vessels		0 or 1 vessel,		
$X_7$	Anchored in the	3	2 to 3 vessels,		
	Zone		more than 3 vessels		
			Fall,		
v	Sacon	1	Winter,		
Λ8	Season	4	Spring,		
			Summer		

Table 3.4 - Situational attributes influencing instigators, accident occurrence and the

consequences

Using all these situational attributes the risk equation can be revised to represent the effects of vessel attributes and environmental factors. Equation 3.8 expresses risk of a vessel *v* as  $R_v(\underline{X}_v)$  based on the situational attribute set  $X_v$ .

$$R_{\nu}(\underline{X}_{\nu}) = \sum_{k} \sum_{j} \sum_{i} E[\mathcal{Q}_{k,j,\nu} \mid C_{k,\nu}, A_{j,\nu}, \underline{X}_{\nu}] \times \Pr(C_{k,\nu} \mid A_{j,\nu}, \underline{X}_{\nu}) \times \Pr(A_{j,\nu} \mid I_{i,\nu}, \underline{X}_{\nu}) \times \Pr(I_{i,\nu}, \underline{X}_{\nu})$$
(3.8)

The approach to evaluate risks in DRB is hybrid in the sense that it involves both a mathematical risk model and the simulation model presented earlier. These two models work in lock step in such a way that the simulation model generates all possible situations and passes them on to the mathematical model for risk evaluations. Based on geography and the existing terminals, DRB is divided into 6 zones as shown in Figure 4.6. By repeating the risk evaluation process at every short time interval (e.g. 60 minutes), it is possible to generate the zone-based risk profile of the entire river.



Figure 3.7 - Delaware River and Bay divided into 6 zones

#### **3.4.** Mathematical Risk Model

The underlying mathematical risk formulation for a set of vessels in a zone is given in Equations 3.9 and 3.10. This formulation represents the instantaneous risk for a given zone s based on the states of the situational attributes as observed at a given instance.

$$R_{s}(\underline{X}) = \sum_{\nu \in \mathcal{Q}_{s}} \sum_{j \in \mathcal{A}} \sum_{k \in \mathcal{C}_{j}} E\left[Q_{k,j,\nu} \mid C_{k,\nu}, A_{j,\nu}, \underline{X}_{\nu}\right] \times \Pr\left(C_{k,\nu} \mid A_{j,\nu}, \underline{X}_{\nu}\right) \times \Pr\left(A_{j,\nu} \mid \underline{X}_{\nu}\right) \quad (3.9)$$

where

$$\Pr\left(A_{j,\nu} \left| \underline{X}_{\nu} \right.\right) = \sum_{i \in \mathcal{I}_{j}} \Pr\left(A_{j,\nu} \left| I_{i,\nu}, \underline{X}_{\nu} \right.\right) \times \Pr\left(I_{i,\nu} \left| \underline{X}_{\nu} \right.\right)$$
(3.10)

and

s: zone no,

v: vessel no,

*j* : accident type,

*k* : consequence type,

 $\underline{X}_{v}$ : Situational attribute set regarding vessel v in zone s,

 $I_{i,v}$ : Instigator type *i*, regarding vessel *v* in zone *s*,

- $A_{i,v}$ : Accident type *j* regarding vessel *v* in zone *s*,
- $C_{k,v}$ : Consequence type k regarding vessel v in zone s,

 $Q_{k,j,v}$ : Impact of consequence type k due to accident type j regarding vessel v in zone s,

 $\mathcal{J}_{i}$ : {1,..,5} is the set of instigators for accident type *j*,

 $e_j$ : {1,...,3} is the set of consequences for accident type j,

 $\boldsymbol{a}$ : {1,..,6} is the set of accidents,

 $v_s$ : is the set of vessels navigating in zone *s* at the observed instance.

Finally,  $E\left[Q_{k,j,\nu}|C_{k,\nu},A_{j,\nu},\underline{X}_{\nu}\right]$  is the expected consequence given the accident and the set of situational attributes and  $\Pr\left(A_{j,\nu}|\underline{X}_{\nu}\right)$  is the probability of accident occurrence given the set of situational attributes. Note that, Equation 3.9 evaluates risk  $R_s(\underline{X})$  as the overall expected consequence based on all possible accidents for each vessel  $\nu$  in zone s.

Based on the above risk formulation, there are number of questions to be answered in order to quantify risks as shown below:

- 1. How frequent does any particular situation occur?
- 2. For a given situation, how often do instigators occur?
- 3. If an instigator occurs, how likely is a particular accident?
- 4. If an accident occurs, what would be the expected damage to human life, environment and property?

In this study, risks are quantified based on historical accident data, expert judgment elicitation and the simulation model of vessel traffic in the Delaware River and Bay introduced earlier. The main use of the simulation model is to generate all the possible situations in a realistic manner (recall 25,920 situations mentioned earlier) and to make the underlying mathematical calculations. Historical accident data provides the

probabilities for instigators, accidents and consequences. At last, expert judgment elicitation provides the link between all possible situations and probabilities associated with these situations.

As introduced in Figure 3.7, Delaware River is divided into 6 zones in the simulation model. The risk in each zone is calculated based on a snapshot taken at every properly chosen  $\Delta t$  time units. In a snapshot, situational attributes for each vessel in a specified zone is available. Thus, risk contribution of each vessel in a particular zone is calculated and aggregated into the zone risk  $R_s(\underline{X})$ . Although instantaneous risks are not continuously tracked, taking snapshots based on a time interval provides sufficiently random and numerous data points. Therefore, the expected risk for a specific zone is obtained by averaging  $R_s(\underline{X})$  over the number of snapshots taken.

Although historical data provides *expected probability of an instigator occurrence per vessel, expected accident probability given an instigator* and *expected probability of a consequence given an accident* these probabilities clearly affected by different situations. That is, the probability of an instigator to occur during day time compared to night time might be different. Each situation and their levels have different effects on these probabilities. Due to lack of data, given a situation estimation of any probability in this context requires expert judgment elicitation, as also indicated by Mosleh et al., (1988) and Apostolakis (1990).

There are many expert judgment elicitation methods discussed in literature since the application areas have been diverse such as aerospace sector, military intelligence, communication, and probabilistic risk analysis. Cooke (1991) provides a broad discussion on different elicitation methods and on the current practice.

In this study, expert opinion elicitation is performed through direct questioning to evaluate the effects of situations and levels of situations on each instigator, accident given an instigator, and consequence given an accident. Although it is pointed out by Apostolakis (1990) that direct assessment of model parameters should be avoided, due to various number of questions to be asked and limited time of experts, elicitation process has to be simplified and direct questioning is adopted.

The participants in elicitation are the members of the Area Maritime Security Committee including the USCG, and the port stakeholders. The participants have more than 15 years of experience in navigation in waterways and/or in services for ports and terminals. In total, seven experienced mariners, whose backgrounds are given below, filled out the surveys.

- 2 U.S. Coast Guard members including the former Captain of the Port (Sector Delaware Bay), and the Chief of the DE/NJ/PA Maritime Incident Response Team,
- A captain who holds federal license for all pilot service areas in the region,

- A port and supply chain management consultant who conducted port assessments in the U.S and various countries for various agencies including USCG,
- 3 captains from a privately owned company providing tug and tow services in the Delaware River and Bay area.

Although this sample size can be seen small due to the complex nature of elicitation process it was not possible to engage more mariners in the process. However, it is believed that the experience of the participants is strong enough to provide valid responses.

In expert opinion elicitation, there are different techniques that have been used in literature to aggregate multiple experts' responses. Simple averaging techniques, weighting the judgments of experts (Genest and Zidek, 1986), and Bayesian techniques to incorporate abilities of the experts (Clemen and Winkler, 1999; Mendel and Sheridan, 1989) are among these several methods. According to Clemen and Winkler (1999), there is no clear advantage of employing more complex techniques over simple averaging techniques. In this study, the arithmetic mean with equal weights for each expert is decided to be appropriate to aggregate expert responses.

For a given event (instigator, accident or consequence)  $\Phi$ , the effect of a situation (*time of day, tide, vessel class,...* etc.) is represented by  $\beta$  and the effect of a level of a situation (*day / night, high tide / low tide, tanker / general cargo,...* etc.) is represented by X which

is also called cardinality of a level of a situation. In this formulation,  $P_{\Phi}$  is the calibration constant which calibrates the associated probability using historical data.

$$\Pr\left(\Phi \middle| \underline{X}\right) = P_{\Phi}(\underline{\beta}^{T} \underline{X}) = P_{\Phi}(\beta_{1}X_{1} + \dots + \beta_{n}X_{n})$$
(3.11)

This formulation is similar to the proportional hazards model originally proposed by Cox (1972). On its original, the proportional hazards model is used to describe the hazard rate (at time t) behaving exponentially with changes in explanatory variables. In maritime domain, a similar accident probability model was proposed by Roeleven (1995), and later used by Merrick et al. (2000) and van Dorp et. al. (2001) in their maritime risk analysis studies. In this study, the exponential form is not adopted due to tremendous increase in the probabilities at the higher values of explanatory variables.

### 3.4.1. Probability of Instigator Given Situation

Based on the discussion above, the probability of an instigator given a particular situation can be estimated using the following formulation.

$$\Pr\left(I_{i} \left| \underline{X}_{i} \right) = P_{i} \cdot \left(\underline{\beta}_{i}^{T} \underline{X}_{i}\right)$$
(3.12)

Through expert judgment elicitation process,  $\beta$  and X values are obtained and directly used in the risk formulations. Sample questionnaires used in expert elicitation to collect  $\beta$  and X values are given in Figure 3.8 and Figure 3.9, respectively.

In  $\beta$  questionnaires for instigators, the effect of a situational attribute on the occurrence of an instigator in a particular vessel is asked to the experts. Experts are expected to put a value between 0 (no relation) and 100 (direct relationship / correlation) to the blocks provided. For some questions, blocks are grayed out since the combination being measured by that block would be unlikely or impossible to occur. However, answers are still permitted if the experts think that there might be a relation. While evaluating risks, situational attribute values shown in Figure 3.8 are averaged over individual responses and later scaled down to less than 1.0.

		Instigator						
Situational Attributes	HE	PF	SF	EF	OSF			
1. Time of Day	80	10	10	10	10			
2. Tide	80	25	25	10	5			
3. (Your) Vessel Status (e.g. Docked, Underway, Anchored)	90	90	90	90	90			
4. (Your) Vessel Class (e.g. General Cargo, Dangerous Cargo)	50	20	20	20	20			
5. Zone (e.g. 1,2,3,4,5,6)	80	10	10	10	10			
6. No. of Vessels Underway within 5 NM of your position	85	10	10	10	10			
7. No. of Vessels Anchored within your Zone	60	10	10	10	10			
8. Season	75	30	30	10	50			

Figure 3.8 - Sample questionnaire for assessing effect of situational attributes on instigator occurrence

In X (cardinality) questionnaires, the importance of a level of a situational attribute on the occurrence of an instigator in a particular vessel is asked to the experts as given in Figure 3.9. Experts are again expected to put a value between 0 (no relation) and 100 (direct relationship / correlation) to the blocks provided where grayed out blocks are still optional. In order to simplify the questionnaires, vessel type question is separately asked

for any type of instigator. However, these answers are weighted using vessel class values and replaced to be used in the formulation.

		Instigator						
	HE	PSF	OSF					
1. Time of Day				-				
a. Day	30	30	10	]				
b. Night	80	50	50					
2. Tide								
a. High	50	10	10	]				
b. Low	80	30	10					
3. (Your) Vessel Status								
a. Docked	0	0	10	]				
b. Underway	90	90	50	]				
c. Anchored	30	0	10					
4. (Your) Vessel Class								
a. General Cargo	50	50	50	III. Hannan Ernan				
b. Dangerous Cargo	60	40	40	<b>HE:</b> Human Error				
5. Zone (Geographical – Infrastructure only)								
a. 1	50	50	10	<b>PSF:</b> Propulsion Failure or				
b. 2	65	60	20	Steering Failure				
c. 3	60	60	20					
d. 4	70	60	20	<b>OSF:</b> Electrical / Electronic				
e. 5	70	60	20	Failure or Other Syster	n			
f. 6	60	60	20	Failures				
6. No. of Vessels Underway within 5 NM				i unulos				
of your position				Vessel Type	Instigator			
a. 0-1	60	20	10	Vesser Type	mstigator			
b. 2-3	70	40	20	1. General Cargo < 150 (m)	60			
c. more than 3	75	50	20	2. General Cargo ≥ 150 (m)	50			
7. No. of Vessels Anchored within your				3. Tugboat / Barge	80			
Zone				4. Passenger ≥ 100 GT	10			
a. 0-1	20	10	10	5. Petroleum Tanker < 200 (m)	30			
b. 2-3	30	20	10	C Detrolour Tanker 200 (m)	20			
c. more than 3	50	30	10	6. Petroleum Tanker ≥ 200 (m)	20			
8. Season		1	1	7. Chemical Tanker < 150 (m)	30			
a. Fall	60	30	10	8. Chemical Tanker ≥ 150 (m)	20			
b. Winter	80	50	20	9. LNG / LPG	10			
c. spring	70	50	10	10 Lightering Barge	90			
a. summer	50	20	10	TO' FIGHTEHING DAIRE	50			

Figure 3.9 - Sample questionnaire for assessing the effects of levels of situational attributes on instigator occurrence

Once all the responses are aggregated from the questionnaires and the  $\beta$  and the X parameters are obtained, these parameters are inputted to the simulation model to be used

$$\Pr\left(Human \ Error_{\nu} \left| \underline{X}_{\nu}^{HE} \right. \right) = P_{HE} \cdot \left( \sum_{h=1}^{n} \beta_{h}^{HE} X_{h,\nu}^{HE} \right)$$
(3.13)

where  $P_{HE}$  is the calibration constant for *Human Error* (*HE*),  $\beta_h^{HE}$  is the categorical effect of the situational attribute *h* on the occurrence of *Human Error* (*HE*), and  $X_{h,v}^{HE}$  is the cardinality value (importance) of the level of the situational attribute *h* as the vessel *v* observes on the occurrence of *Human Error* (*HE*). Clearly, other instigators have similar equations.

## 3.4.2. Probability of Accident Given Instigator and Situation

The probability of an accident given an instigator taking place in a particular situation can be estimated using the formulation given below.

$$\Pr\left(A_{j}\left|I_{i},\underline{X}_{j,i}\right.\right) = P_{j,i} \cdot \left(\underline{\beta}_{j,i}^{T} \underline{X}_{j,i}\right)$$

$$(3.14)$$

Through the expert judgment elicitation process, again  $\beta$  and X values are obtained and directly used in the formulations. Sample questionnaires to collect  $\beta$  and X values are given in Figure 3.10 and Figure 3.11 respectively.

 $\beta$  questionnaires for accidents (Figure 3.10) are prepared for all accident types separately. In questions, given an instigator taking place on a particular vessel, the effect of a situational attribute on the likelihood of an accident is asked to the experts.

	Collision   Instigators				
Situational Attributes	HE <sup>C</sup>	PF <sup>C</sup>	SF <sup>C</sup>	EF <sup>C</sup>	OSF <sup>C</sup>
1. Time of Day	75	30	30	40	10
2. Tide	80	70	70	10	10
3. (Your) Vessel Status (e.g. Docked, Underway, Anchored)	90	90	90	40	40
4. (Your) Vessel Class (e.g. General Cargo, Dangerous Cargo)	20	20	20	20	20
5. Zone (e.g. 1,2,3,4,5,6)	90	90	90	20	10
6. No. of Vessels Underway within 5 NM of your position	90	90	90	20	10
7. No. of Vessels Anchored within your Zone	90	90	90	20	10
8. Season	80	70	70	20	10

Figure 3.10 - Sample questionnaire for assessing effect of situational attributes on collision occurrence

X (cardinality) questions for accidents are combined into one questionnaire for any type of accident as given in Figure 3.11. The main reason for this simplification is due to the assumption that the levels of situational attributes have very similar effects on all accident types in consideration. In questions, given an instigator taking place on a particular vessel, the importance of attribute levels on the likelihood of an accident is asked to the participants.

	Accio	dent   Insti	gator				
	HE	PSF	OSF				
1. Time of Day							
a. Day	70	70	10				
b. Night	90	90	50				
2. Tide	]						
a. High	40	40	10				
b. Low	60	60	20				
3. (Your) Vessel Status							
a. Docked	90	0	10				
b. Underway	70	90	10				
c. Anchored	90	0	10				
4. (Your) Vessel Class							
a. General Cargo	50	50	10	HE. Homen Emer			
b. Dangerous Cargo	90	90	30	<b>HE:</b> Human Error			
5. Zone (Geographical – Infrastructure only)							
a. 1	20	30	10	<b>PSF:</b> Propulsion Failure or			
b. 2	20	30	15	Steering Failure			
с. 3	50	70	20				
d. 4	50	70	20	<b>OSF:</b> Electrical / Electronic			
e. 5	50	70	20	Failure or Other Syste	em		
f. 6	20	30	15	Failures			
6. No. of Vessels Underway within 5 NM	1			T unuios			
of your position					Assidant   Instigator		
a. 0-1	50	50	10	vesser type	Accident   Instigator		
b. 2-3	70	60	20	1. General Cargo < 150 (m)	60		
c. more than 3	90	90	20	2. General Cargo ≥ 150 (m)	50		
7. No. of Vessels Anchored within your				3. Tugboat / Barge	70		
Zone		1	1	4. Passenger ≥ 100 GT	50		
a. 0-1	50	50	10	5 Petroleum Tanker < 200 (m)	60		
b. 2-3	60	60	20		50		
c. more than 3	70	70	20	6. Petroleum Tanker ≥ 200 (m)	50		
8. Season				7. Chemical Tanker < 150 (m)	60		
a. Fall	60	10	0	8. Chemical Tanker ≥ 150 (m)	50		
b. Winter	80	30	10	9. LNG / LPG	50		
c. Spring	70	10	0	10 Lightoring Pargo	80		
ld. Summer	20	10	0	TO' FIRITIGHTING DOLLE	00		

Figure 3.11 - Sample questionnaire for assessing the effects of levels of situational attributes on accident occurrence

After aggregation, the  $\beta$  and the X parameters are inputted to the simulation model to be used for probability estimations for accidents in a similar way to instigators. The probability of an accident such as *Collision* (*C*) given an instigator such as *Human Error* (*HE*) has already happened on a vessel v can be described as below.

$$\Pr\left(Collision_{\nu} | HE_{\nu}, \underline{X}_{\nu}\right) = P_{C,HE} \cdot \left(\sum_{h=1}^{n} \beta_{h}^{C,HE} X_{h,\nu}^{C,HE}\right)$$
(3.15)

where  $P_{C,HE}$  is the calibration constant for the probability expression *Collision (C) given Human Error (HE) has happened*,  $\beta_h^{C,HE}$  is the categorical effect of the situational attribute *h* on the likelihood of *Collision (C) given Human Error (HE)*, and  $X_{h,v}^{C,HE}$  is the cardinality value (importance) of the level of the situational attribute *h* as the vessel *v* observes on the likelihood of *Collision (C) given Human Error (HE)*. Then it follows form Equation 3.3 that, the unconditional probability of an accident such as *Collision (C)* on a vessel *v* is described in Equation 3.16. Also, as it follows from Equations 3.14 and 3.15 that, this probability is described in the simulation model as in Equation 3.17.

$$Pr(Collision_{v} | \underline{X}_{v}) = Pr(Collision_{v} | HE_{v}, \underline{X}_{v}) \times Pr(HE_{v} | \underline{X}_{v}) + Pr(Collision_{v} | PF_{v}, \underline{X}_{v}) \times Pr(PF_{v} | \underline{X}_{v}) + Pr(Collision_{v} | SF_{v}, \underline{X}_{v}) \times Pr(SF_{v} | \underline{X}_{v}) + Pr(Collision_{v} | EF_{v}, \underline{X}_{v}) \times Pr(EF_{v} | \underline{X}_{v}) + Pr(Collision_{v} | OSF_{v}, \underline{X}_{v}) \times Pr(OSF_{v} | \underline{X}_{v})$$
(3.16)

$$Pr(Collision_{v} | \underline{X}_{v}) = P_{C,HE} \cdot (\sum_{h=1}^{n} \beta_{h}^{C,HE} X_{h,v}^{C,HE}) \times P_{HE} \cdot (\sum_{h=1}^{n} \beta_{h}^{HE} X_{h,v}^{HE}) + P_{C,PF} \cdot (\sum_{h=1}^{n} \beta_{h}^{C,PF} X_{h,v}^{C,PF}) \times P_{PF} \cdot (\sum_{h=1}^{n} \beta_{h}^{PF} X_{h,v}^{PF}) + P_{C,SF} \cdot (\sum_{h=1}^{n} \beta_{h}^{C,SF} X_{h,v}^{C,SF}) \times P_{SF} \cdot (\sum_{h=1}^{n} \beta_{h}^{SF} X_{h,v}^{SF}) + P_{C,EF} \cdot (\sum_{h=1}^{n} \beta_{h}^{C,EF} X_{h,v}^{C,EF}) \times P_{EF} \cdot (\sum_{h=1}^{n} \beta_{h}^{EF} X_{h,v}^{EF}) + P_{C,OSF} \cdot (\sum_{h=1}^{n} \beta_{h}^{C,OSF} X_{h,v}^{C,OSF}) \times P_{OSF} \cdot (\sum_{h=1}^{n} \beta_{h}^{OSF} X_{h,v}^{OSF})$$
(3.17)

## 3.4.3. Probability of Consequence Given Accident and Situation

The probability of a consequence given an accident has happened in a particular situation can be estimated using the formulation given below.

$$\Pr\left(C_{k}\left|A_{j},\underline{X}_{k,j}\right)=P_{k,j}\cdot\left(\underline{\beta}_{k,j}^{T}\underline{X}_{k,j}\right)$$
(3.18)

Through expert judgment elicitation process, again  $\beta$  and X values are obtained, and directly used in the formulation. Sample questionnaires to collect  $\beta$  and X values are given in Figure 3.12 and Figure 3.13, respectively.

 $\beta$  questionnaires for consequences are prepared based on all accident types separately. In questions, given an accident has happened, the effect of a situational attribute on the likelihood of the consequence is asked to the experts.

	Consequences   Collision			
Situational Attributes	HC	EnvD	ProD	
1. Time of Day	90	80	90	
2. Tide	10	95	30	
3. (Your) Vessel Status (e.g. Docked, Underway, Anchored)	90	80	80	
4. (Your) Vessel Class (e.g. General Cargo, Dangerous Cargo)	90	95	90	
5. Zone (e.g. 1,2,3,4,5,6)	80	90	90	
6. No. of Vessels Underway within 5 NM of your position	90	70	90	
7. No. of Vessels Anchored within your Zone	10	10	10	
8. Season	80	80	70	

Figure 3.12 - Sample questionnaire for assessing the effects of situational attributes on consequence severity

X (cardinality) questions for consequences are combined into one questionnaire based on any type of accident. The main reason for this simplification is due to the assumption that the levels of situational attributes have very similar effects on all consequences in consideration. In questions, given an accident has happened, the importance of attribute characteristics on the likelihood of the consequence is asked to the participants.

	Consequence   Accident						
	Human	Environmental	Property				
1. Time of Day	Casualty	Damage	Damage				
a. Day	50	50	50				
b. Night	90	90	90				
2. Tide				,			
a. High	10	10	10				
b. Low	10	60	70				
3. (Your) Vessel Status							
a. Docked	10	40	20				
b. Underway	90	70	90				
c. Anchored	50	40	60				
4. (Your) Vessel Class					Conse	quence   Aq	cident
a. General Cargo	50	40	9	Manage Trung		Em. D	DeeD
b. Dangerous Cargo	70	90	-	vesser type	HC	ENVD	ProD
5. Zone (Geographical – Infrastructure only)			1. Gene	eral Cargo < 150 (m)	50	60	60
a. 1	80	70	2. Gene	eral Cargo≥150 (m)	50	70	70
b. 2	70	80	- 3. Tugb	ooat / Barge	60	70	70
c. 3	75	80	-4. Pass	enger≥100 GT	100	30	30
d. 4	75	80	-5. Petro	oleum Tanker < 200 (m)	80	80	80
e. 5	75	80	-6. Petro	oleum Tanker ≥ 200 (m)	80	80	80
f. 6	60	80	7. Cher	mical Tanker < 150 (m)	80	80	80
6. No. of Vessels Underway within 5			8. Cher	mical Tanker≥150 (m)	80	80	80
NM of your position			9. LNG	/ LPG	90	20	90
a. 0-1	50	60	10. Ligh	ntering Barge	20	90	90
b. 2-3	60	70	60				
c. more than 3	50	70	70				
7. No. of Vessels Anchored within							
your Zone							
a. 0-1	70	50	50				
b. 2-3	70	50	60				
c. more than 3	75	50	70				
8. Season							
a. Fall	50	50	60				
b. Winter	90	90	60				
c. Spring	50	70	70				
d. Summer	20	50	90				



on consequence severity

After aggregation of responses, the  $\beta$  and the *X* parameters for the consequences are inputted to the simulation model to be used for probability estimations. The probability of a consequence such as *Environmental Damage* (*EnvD*) given an accident such as *Collision* (*C*) has already happened on a vessel *v* can be described as below.

$$\Pr\left(EnvD_{\nu} \middle| Collision_{\nu}, \underline{X}_{\nu}\right) = P_{EnvD,C} \cdot \left(\sum_{h=1}^{n} \beta_{h}^{EnvD,C} X_{h,\nu}^{EnvD,C}\right)$$
(3.19)

where  $P_{EnvD,C}$  is the calibration constant for the probability expression *Environmental* Damage (EnvD) given Collision (C) has happened,  $\beta_h^{EnvD,C}$  is the categorical effect of the situational attribute h on the likelihood of *Environmental Damage* (EnvD) given Collision (C), and  $X_{h,v}^{EnvD,C}$  is the cardinality value (importance) of the level of the situational attribute h as the vessel v observes on the likelihood of *Environmental* Damage (EnvD) given Collision (C). Then it follows form Equation 3.5 that, the unconditional probability of a consequence such as *Environmental Damage* (EnvD) on a vessel v is described in Equation 3.20. Also, as it follows from Equations 3.17 and 3.19 that, this probability is described in the simulation model as in Equation 3.21.

$$\Pr(EnvD_{\nu}|\underline{X}_{\nu}) = \Pr(EnvD_{\nu}|Collision_{\nu}, \underline{X}_{\nu}) \times \Pr(Collision_{\nu}|\underline{X}_{\nu}) + \Pr(EnvD_{\nu}|Allision_{\nu}, \underline{X}_{\nu}) \times \Pr(Allision_{\nu}|\underline{X}_{\nu}) + \Pr(EnvD_{\nu}|Grounding_{\nu}, \underline{X}_{\nu}) \times \Pr(Grounding_{\nu}|\underline{X}_{\nu}) + \Pr(EnvD_{\nu}|Fire / Explosion_{\nu}, \underline{X}_{\nu}) \times \Pr(Fire / Explosion_{\nu}|\underline{X}_{\nu}) + \Pr(EnvD_{\nu}|Sink / Cpsz / Fld_{\nu}, \underline{X}_{\nu}) \times \Pr(Sink / Cpsz / Fld_{\nu}|\underline{X}_{\nu}) + \Pr(EnvD_{\nu}|Oil Spill_{\nu}, \underline{X}_{\nu}) \times \Pr(Oil Spill_{\nu}|\underline{X}_{\nu})$$
(3.20)

$$\Pr\left(EnvD_{\nu} | \underline{X}_{\nu}\right) = P_{EnvD,C} \cdot \left(\sum_{h=1}^{n} \beta_{h}^{EnvD,C} X_{h,\nu}^{EnvD,C}\right) \times \Pr\left(Collision_{\nu} | \underline{X}_{\nu}\right) \\ + P_{EnvD,A} \cdot \left(\sum_{h=1}^{n} \beta_{h}^{EnvD,A} X_{h,\nu}^{EnvD,A}\right) \times \Pr\left(Allision_{\nu} | \underline{X}_{\nu}\right) \\ + P_{EnvD,G} \cdot \left(\sum_{h=1}^{n} \beta_{h}^{EnvD,G} X_{h,\nu}^{EnvD,G}\right) \times \Pr\left(Grounding_{\nu} | \underline{X}_{\nu}\right) \\ + P_{EnvD,F/E} \cdot \left(\sum_{h=1}^{n} \beta_{h}^{EnvD,F/E} X_{h,\nu}^{EnvD,F/E}\right) \times \Pr\left(Fire / Explosion_{\nu} | \underline{X}_{\nu}\right) \\ + P_{EnvD,S/C/F} \cdot \left(\sum_{h=1}^{n} \beta_{h}^{EnvD,S/C/F} X_{h,\nu}^{EnvD,S/C/F}\right) \times \Pr\left(Sink / Cpsz / Fld_{\nu} | \underline{X}_{\nu}\right) \\ + P_{EnvD,OS} \cdot \left(\sum_{h=1}^{n} \beta_{h}^{EnvD,OS} X_{h,\nu}^{EnvD,OS}\right) \times \Pr\left(Oil Spill_{\nu} | \underline{X}_{\nu}\right)$$

# **3.4.4.** Consequence Impact Levels

Expected impact of a consequence given an accident and a situation in a particular situation can be expressed using the formulation given below.

$$E[Q_{k,j,\nu} | C_{k,\nu}, A_{j,\nu}, \underline{X}_{\nu}] = \sum_{Q_{k,j,\nu}} Q_{k,j,\nu} \times \Pr(Q_{k,j,\nu} | C_{k,\nu}, A_{j,\nu}, \underline{X}_{\nu})$$
(3.22)

where  $Q_{k,j,\nu}$  is the random variable representing the impact level of consequence type k due to accident type j having the probability mass distribution  $Pr(Q_{k,j,\nu} | C_{k,\nu}, A_{j,\nu}, \underline{X}_{\nu})$ .

Evaluation of consequences is a major challenge in risk analysis. Below we summarize our efforts to quantify accident consequences in the DRB area. All consequences are evaluated for their direct impacts in dollar terms, however their cascading and secondary impacts are not considered.

# 3.4.4.1. Quantification of Human Casualty

When there is human casualty after an accident, number of injuries and/or deaths are estimated from the empirical distribution based on historical data. Injury histogram given in Figure 3.14 is for all types of accidents. In addition to injury, data suggests a 10% death rate per incident for the Fire/Explosion case only.



Figure 3.14 - Histogram showing number of injuries per incident when there is human casualty in the historical data from years 1992 to 2008 (Source: USCG)

The U.S National Safety Council comprehensive cost values from 2009 (NSC, 2009) are used to estimate total human casualty costs. Table 3.5 shows the average comprehensive costs for injuries based on their severity.

 Table 3.5 - U.S. National Safety Council 2009 values for average comprehensive cost by injury severity (Source: NSC, 2009)

Average Comprehensive Cost by l	Injury Severity
Death	\$4,300,000
Non-incapacitating evident injury	\$55,300
No injury	\$2,400

## **3.4.4.2.** Quantification of Environmental Damage

Environmental damage costs are estimated based on oil spill historical data per vessel type. It is independent of the accident type since historical data does not suggest a significant difference. For a given incident, total oil spill is estimated from empirical distributions per vessel type, and comprehensive costs from Table 3.6 below are used to estimate the total costs. Oil spill distributions are obtained from the historical data for tankers, tugs/barges, and all other vessel types separately. Oil spill data distributions for different types of vessels are given in Figure 3.15 to Figure 3.17.



Figure 3.15 - Histogram showing gallons spilled from tankers per incident when there is environmental damage in the historical data of years 1992 to 2008 (Source: USCG)



Figure 3.16 - Histogram showing gallons spilled from tugs and barges per incident when there is environmental damage in the historical data of years 1992 to 2008 (Source:

USCG)



Figure 3.17 - Histogram showing gallons spilled from other cargo vessels per incident when there is environmental damage in the historical data of years 1992 to 2008 (Source: USCG)

Comprehensive oil spill costs per gallon covering response costs, environmental damage costs, and the socioeconomic costs are given in Table 3.6 based on (Etkin, 2004). Note that comprehensive costs are adjusted to 2011 values with inflation rates.

Oil Spill (Gallons)	Average Response Cost/Gallon (\$)	Environmental Cost/Gallon (\$)	Socioeconomic Cost/Gallon (\$)	Total Cost/Gallon (\$) (Present Value)
< 500	199	90	50	401.98
500 - 1000	197	87	200	573.92
1000 - 10K	195	80	300	681.83
10K - 100K	185	73	140	471.95
100K - 1000K	118	35	70	264.43
> 1M	82	30	60	203.96

Table 3.6 - Comprehensive oil spill costs based on gallons spilled (Source: Etkin, 2004)

## 3.4.4.3. Quantification of Property Damage

Property damage costs are estimated based on historical data for a given accident type. For each accident type, empirical distributions are fit to estimate total property damage costs. Note that costs from the historical data are adjusted to 2011 values by applying inflation rates. Figure 3.18 shows the histogram for aggregated property damage data for all accident types.



Figure 3.18 - Histogram showing costs per incident when there is property damage in the historical data of years 1992 to 2008 (Source: USCG)

### 3.4.5. Calibration of Probabilities

The validation process of the accident probabilities in risk calculations involves a calibration process. It is about comparing estimated probabilities from the simulation

model with the corresponding probabilities from the historical data, to the extent of their availability. This is achieved by making a preliminary simulation run with the calibration constants ( $P_{\Phi}$ 's for a given event  $\Phi$ ) in the risk model being unity. After running the model long enough, each probability (such as probability of *Collision given Human Error*) is averaged over time and over all situations in the model. This measure is a proper value to be compared with the same probability obtained from the historical data. Hence, to calculate the calibration constant, every probability from the historical data is divided by its corresponding counterpart from the model. The ratio is the calibration constant and replaces the ones in the preliminary run of the model, making the model ready for risk calculations. In essence, this operation is described below.

Let  $Pr(\Phi)$  be the probability of an event (*instigator*, *accident given instigator* or *consequence given accident*) from historical data, and let  $\hat{\theta}$  be the estimator of the corresponding probability in the simulation model. Also  $Pr(\Phi|\underline{X}_v)$  be the unknown probability of the event based on a situation observed by vessel v, and  $\theta_v = P_{\Phi} \cdot (\underline{\beta}^T \underline{X}_v)$  be the corresponding probability calculated in the simulation. According to the strong law of large numbers, the sample average, as a long-term average over all possible situations, converges almost surely to the expected value.

$$\Pr(\Phi) \simeq \hat{\theta}$$

$$\Pr(\Phi) = \lim_{n \to \infty} \frac{\sum_{\nu=1}^{n} \Pr(\Phi | \underline{X}_{\nu})}{n}$$

$$\hat{\theta} = \lim_{n \to \infty} \frac{\sum_{\nu=1}^{n} P_{\Phi} \cdot (\underline{\beta}^{T} \underline{X}_{\nu})}{n}$$
(3.23)

Then let  $\overline{\theta}'$  be the estimate from the preliminary simulation run as a long-term average over all possible situations in which there are *n* observations. If we set  $P'_{\Phi} = 1$  in the preliminary run, then  $P_{\Phi}$  can be estimated from the ratio  $\frac{\Pr(\Phi)}{\hat{\theta}'}$ , as shown in the equations below.

$$\overline{\theta}' = \frac{\sum_{\nu=1}^{n} P_{\Phi}' \cdot (\underline{\beta}^{T} \underline{X}_{\nu})}{n}$$

$$\overline{\theta}' = P_{\Phi}' \frac{\sum_{\nu=1}^{n} (\underline{\beta}^{T} \underline{X}_{\nu})}{n}, \quad P_{\Phi}' = 1$$

$$\Pr(\Phi) \approx P_{\Phi} \cdot \frac{\sum_{\nu=1}^{n} (\underline{\beta}^{T} \underline{X}_{\nu})}{n}$$

$$\Pr(\Phi) \approx P_{\Phi} \cdot \overline{\theta}'$$

$$P_{\Phi} \approx \frac{\Pr(\Phi)}{\overline{\theta}'}$$
(3.24)

### **3.5.** Risk Evaluations

The aforementioned risk model (Equation 3.9) is integrated into the simulation model which is capable of producing all possible situations regarding both the vessel traffic and the situations in the river. The mathematical risk model and the simulation model work hand in hand in such a way that the risk model responds with the corresponding risk evaluation for every possible situation generated in the simulation model. This process is carried out at every short time interval (i.e., 60 minutes) at each zone to produce a temporal risk profile of the entire river. At every time step, using the situation attribute values, the risk model calculates probabilities of all types of accidents to occur given the situation at the time. Then the model uses these probabilities to calculate corresponding risks. Clearly, this is a process that is computationally intensive especially if the risk profiles are required to be precise indicating frequent evaluations. Results of risk calculation in the model are saved in an output file for further analysis and demonstration purposes.

### **3.6.** Numerical Results

The results of the risk model are presented and examined in this part to provide an insight of the risk profile for the current situation of the river based on past data. All risk estimates are expressed in financial terms that are in dollars.

There are two statistics used in this section to evaluate risks. The first one is average risk which is the average of all instantaneous risk values observed in the given time frame.

This statistic is helpful to evaluate how riskier a situation or a scenario when compared to others. On the other hand, the maximum risk, which is the maximum of all instantaneous risk values observed, is the indicator of a catastrophe. In general, it can be said that the maximum risk carry the information of a possibility rather than likelihood. In this study, both the average risk and the maximum risk statistics are considered to make evaluations and comparisons.

The simulation model is run for 1 year with 100 replications to obtain the current risk profile in this section. The average risk and maximum risk statistics are averaged over 100 replications and their averages, 95% confidence intervals (half-width), minimum and maximum values across replications are provided. Notice that, the simulation model is built using the actual data of years between 2004 and 2008, thus a year in the simulation run is an average year representing the average vessel movements within these years.

#### **3.6.1.** Current Risks

In order to illustrate instantaneous risk concept, Figure 3.19 displays a 3D risk profile of DRB throughout a 24-hour time horizon. Instantaneous risk values are observations from the risk model obtained at each snapshot throughout the simulation run. In this figure, the instantaneous risk values of a full year of one replication simulation run are mapped into a 24-hour time frame, such that the "Time of Day" axis shows the real time of day when the corresponding risk value has been observed by the model. Looking at this figure from



Figure 3.19 - 3D instantaneous risk profile of Delaware River and Bay based on zones and time of day

Average zone risk is obtained by taking the average of instantaneous risk observations at the end of a simulation replication. After a simulation run is over, these values are averaged across all replications. Table 3.7 shows the average risks at each zone in DRB. This table indicates zone 1, the entrance region, has the highest risk in DRB followed by zone 4, and zone 3.

	Average	Half Width (95% CI)	Minimum	Maximum
Zone 1	85204	2068.70	66820	122500
Zone 2	20564	222.35	18256	22952
Zone 3	37032	560.95	31279	48805
Zone 4	46546	471.02	41940	53842
Zone 5	18231	246.20	15827	21817
Zone 6	1595	30.30	1153	1967

Table 3.7 - Average zone risks (\$)

\* Risk is defined as the sum of expected consequences expressed in dollar terms.

In Figure 3.20 and in Table 3.8 the average risks are classified by the consequence types. In Figure 3.20, the height of each bar shows the average total risk for a given zone in DRB. Again the average risks for zones 1, 3 and 4 are higher than the risks for other zones. Different colors in each bar show the relative importance of the corresponding consequence type in the total risk figure for that zone. Almost in all zones environmental damage (EnvD) is the dominant consequence of all. This is plausible for zones 1, 3 and 4. In zone 1, the risk of environmental damage is high due to a great deal of lightering activity in Big Stone Beach Anchorage. Frequency of visits and length of stay for tankers in zones 3 and 4 are higher than the ones in other zones as a result of higher number of oil terminals. Therefore the probability of occurrence of environmental damage is higher and consequently the expected environmental damage and expected risks are higher in these zones.



Figure 3.20 - Zone risks classified by consequence type

Again in Table 3.8, average risks classified by consequence type are given with their averages, 95% confidence intervals, minimums and maximums over 100 replications. The table indicates a large variability in Environmental Damage (EnvD). The main reason behind is the historical data provide large variability in the oils spills as a result of accidents. This could also be an indication of environmental damage being closely related to response time of the authorities which in return produces a high variability in results in reality.

Consequence	Zone	Average	Half Width	Minimum	Maximum	
			(95% CI)			
Human Casualty	1	1410	20.41	1179	1743	
(HC)	2	385	3.38	341	420	
	3	732	7.00	654	840	
	4	704	8.46	625	843	
	5	732	7.91	639	814	
	6	135	2.64	93	170	
Environmental Damage	1	72237	1881.70	55867	106340	
(EnvD)	2	16992	203.57	14989	19247	
	3	29827	514.38	24914	41018	
	4	39488	412.55	35353	45516	
	5	10557	206.63	8733	14026	
	6	179	3.64	131	223	
Property Damage	1	11557	170.91	9774	14416	
(ProD)	2	3187	25.58	2887	3438	
	3	6472	62.24	5708	7433	
	4	6354	74.04	5617	7482	
	5	6942	72.64	6013	7718	
	6	1281	24.43	924	1587	

Table 3.8 - Average zone risks (\$) classified by consequence type

\* Risk is defined as the sum of expected consequences expressed in dollar terms.

Figure 3.21 shows the same overall risk values as in Figure 3.20, but the average risks are classified based on accident types in each zone. This is to better understand the contribution of each accident to zone risks. As suggested by the figure, Oil Spill (OS) and Grounding (G) seem to be the major accidents having the biggest contributions to risks in DRB. This is apparently reasonable considering the extensive tanker activity and the depth limitations in the river.



Figure 3.21 - Zone risks classified by accident type

Again in Table 3.9, average risks classified by accident type are given with their averages, 95% confidence intervals, minimums and maximums over 100 replications. The table indicates Oil Spill (OS) has the largest variability in risk values. This is plausible since oil spills are closely related to environmental damage, which also showed a high variability in risk values. In addition, oil spill risks are higher in zone 1 and zone 4 where the tanker activity is higher in the river.
Accident	Zone	Average	Half Width (95% CI)	Minimum	Maximum
Collision (C)	1	4544	117.16	3494	6613
	2	1016	12.83	854	1168
	3	1879	32.08	1559	2553
	4	2339	24.51	2102	2692
	5	811	11.95	697	970
	6	57	1.11	41	72
Allision (A)	1	7515	185.88	5944	10656
	2	1734	17.68	1546	1920
	3	3244	50.94	2771	4262
	4	3972	40.31	3534	4726
	5	1722	22.04	1480	1999
	6	179	3.46	129	222
Grounding (G)	1	11379	255.44	9049	15973
	2	2806	26.52	2546	3056
	3	5397	70.93	4695	6811
	4	6267	63.38	5745	7417
	5	3812	41.94	3355	4303
	6	538	10.28	390	663
Fire/Explosion (FE)	1	5669	113.78	4548	7572
	2	1398	12.03	1259	1528
	3	2603	31.58	2195	3120
	4	2859	29.42	2611	3390
	5	1920	20.66	1667	2158
	6	293	5.57	208	367
Sinking/Capsizing/Flooding	1	11592	270.36	9117	16492
(SCF)	2	2734	32.11	2379	3102
	3	4979	74.92	4215	6594
	4	6189	60.95	5566	7110
	5	2500	35.40	2139	2977
	6	233	4.45	169	290
Oil Spill (OS)	1	44504	1139.30	34669	65194
	2	10876	147.22	9334	12582
	3	18930	321.26	15641	25464
	4	24920	282.17	21894	28507
	5	7467	135.29	6195	9635
	6	295	5.64	216	364

Table 3.9 - Average zone risks (\$) classified by accident type

\* Risk is defined as the sum of expected consequences expressed in dollar terms.

Maximum zone risk is obtained by taking the maximum of instantaneous risk observations at the end of a simulation replication. After a simulation run is over, these values are averaged across all 100 replications. Table 3.10 shows the average maximum risks at each zone in DRB. The table exhibits zone 1, has the highest maximum risk in DRB followed by zone 3, zone 4 and zone 2. This can be interpreted as the magnitude of a disaster in zone 1 could be much higher than other zones. An interesting observation at this point could be regarding zone 2 that has similar maximum risk to zones 3 and 4 albeit average risk in zone 2 is much lower than these zones (as given in Table 3.7). This indication can be interpreted as zone 3 and 4 but the magnitude of a disaster that may happen in all these zones are similar to each other.

	Average	Half Width (95% CI)	Minimum	Maximum
Zone 1	1072200	33477.00	778410	1736200
Zone 2	815840	26382.00	621980	1343800
Zone 3	890120	26928.00	670710	1525000
Zone 4	846140	25703.00	592220	1190100
Zone 5	593920	26360.00	399390	998090
Zone 6	23202	2455.60	10311	67104

Table 3.10 - Maximum zone risks (\$)

\* Risk is defined as the sum of expected consequences expressed in dollar terms.

In Table 3.11, maximum risks classified by consequence type are given with their averages, 95% confidence intervals, minimums and maximums over 100 replications. The table exhibits that Environmental Damage (EnvD) has the highest contribution in the maximum risks.

Consequence	Zone	Average	Half Width (95% CI)	Minimum	Maximum
Human Casualty	1	10356	256.33	7775	15724
(HC)	2	6176	169.46	4648	8886
	3	7160	195.32	5390	10198
	4	6609	187.49	5143	10582
	5	5591	123.81	4180	7481
	6	2955	93.69	1992	4559
Environmental Damage	1	1050900	32798.00	763180	1705000
(EnvD)	2	808730	26248.00	613660	1333000
	3	878310	26800.00	660780	1518100
	4	835320	25599.00	585390	1185800
	5	582050	26121.00	389570	982880
	6	19537	2486.90	5931	63640
<b>Property Damage</b>	1	42035	1016.20	33348	58796
(ProD)	2	20916	524.52	16985	31771
	3	28271	709.90	22990	40174
	4	26834	733.09	20868	40949
	5	24702	484.56	19648	31790
	6	9161	285.24	6695	15642

Table 3.11 - Maximum zone risks (\$) classified by consequence type

\* Risk is defined as the sum of expected consequences expressed in dollar terms.

In Table 3.12, maximum risks classified by accident type are given with their averages, 95% confidence intervals, minimums and maximums over 100 replications. From the table, it can be seen that Oil Spill (OS) has the highest contribution to maximum risks. This finding is in line with the disasters that happened in the past decades in DRB. The Grand Eagle accident in 1985, Presidente Rivera in 1989 and recently M/V Athos I in 2005 caused 306,000 gallons, 435,000 gallons and 265,000 gallons of oil spills respectively. The second highest contributor in maximum risks is Sinking/Capsizing/Flooding (SCF) accident class. This is plausible since the extreme consequences related to these accidents could be more severe than others.

Accident	Zone	Average	Half Width (95% CI)	Minimum	Maximum
Collision (C)	1	95249	2658.20	66426	138140
	2	71021	2014.40	50491	98972
	3	80774	2655.80	56170	127450
	4	74520	2609.90	51780	117750
	5	52367	2341.70	34819	98298
	6	1739	193.54	537	4855
Allision (A)	1	138690	4554.90	97694	224370
	2	105400	3748.90	72276	157330
	3	114710	3991.20	83350	180410
	4	107810	3494.00	76469	173830
	5	76291	2988.90	48978	120790
	6	2819	243.91	1454	8883
Grounding (G)	1	159720	5422.50	115730	257870
	2	121460	4074.20	81550	176160
	3	130050	4141.90	95469	194210
	4	121970	3319.20	89696	173050
	5	86847	4007.50	59317	206140
	6	6060	249.69	4246	11841
Fire/Explosion (FE)	1	67864	1897.00	52505	92596
	2	48415	1322.90	32349	64090
	3	55046	1556.70	37817	75944
	4	51497	1840.90	35660	82915
	5	36077	1587.90	21717	57217
	6	3825	127.56	2714	5952
Sinking/Capsizing/Flooding	1	226120	6292.90	171150	308450
(SCF)	2	177490	5937.20	116420	307270
	3	186940	6487.80	111770	275650
	4	176650	5541.10	125720	278170
	5	122690	6024.10	78271	224810
	6	4183	514.69	1595	15240
Oil Spill (OS)	1	981290	30524.00	716300	1513300
	2	789290	26473.00	550830	1331400
	3	841460	27400.00	607450	1515500
	4	792830	23430.00	538720	1097400
	5	562920	24068.00	385390	943380
	6	19078	2461.10	6129	64110

Table 3.12 - Maximum zone risks (\$) classified by accident type

\* Risk is defined as the sum of expected consequences expressed in dollar terms.

Figure 3.22 provides the risk histogram for each zone obtained from the simulation. The histograms showing the risk for zones 2, 5 and 6 exhibit low risk values while zones 1, 3, and 4 display slowly decaying tails to the right, indicating high risks observed in these zones.



Figure 3.22 - Histogram of risks for 6 zones of DRB

Apart from zone risk which is the accumulation of all vessel risks in a zone, average risk per vessel could be another risk measure of interest. This measure may better indicate the severity of situations observed in each zone. Table 3.13 gives the average vessel risks observed in each zone. The table shows, on average a vessel observes the highest risks in zone 1. Possible reasons behind are high tanker activity due to lightering, and high vessel density since 93% of all vessels pass through this zone while entering and leaving the port. On the other hand, the most interesting observation is that, zone 2 is marking the second highest average risks per vessel although the average zone risk is among the lowest for the zone. This is possibly an indication of having the second entrance and exit point for the system in this zone, and this creates a dangerous intersection for the moving vessels due to high vessel density.

	Average	Half Width (95% CI)	Minimum	Maximum
A vessel in Zone 1	10378	84.81	9677	11652
A vessel in Zone 2	8277	71.27	7202	9271
A vessel in Zone 3	6464	74.48	5782	8051
A vessel in Zone 4	7698	62.38	7058	8488
A vessel in Zone 5	2407	27.03	2165	2873
A vessel in Zone 6	1019	2.54	992	1051

Table 3.13 - Average risk (\$) per vessel in each zone

\* Risk is defined as the sum of expected consequences expressed in dollar terms.

As a result of the current risk evaluations, zone 1, zone 3 and zone 4 are the regions showing the highest risks in Delaware River and Bay. In terms of accidents, oil spill and grounding are the highest risk generating accidents. In terms of consequences, environmental damage seems to have the highest impact. Some of these findings can be supported by historical accident data in the river or through feedbacks of experts. However, a structured validation of these results is extremely difficult. Merrick et al. (2002) discuss difficulty of validation in risk assessment studies due to aggregated nature of input information coming from several sources. On the other hand, the risk model implemented in the simulation model is verified in several steps to check if it is working the way it is intended to. The risk model is developed, and deployed into the simulation model in stages in which each stage is individually examined. In addition, the risk model is run under extreme conditions (such as minimum and maximum possible values of parameters) to test if it is generating plausible results. In this regard, the risk model has passed all the verification tests and subjective validation steps; however, it is not possible to compare model outputs to the actual data as a conclusive validation test due to unavailability of such data.

### **3.7.** Risk Evaluation of Deepening Related Scenarios

In this section, a scenario analysis is presented focusing on investigating effects of deepening on risk measures based on scenarios presented in Section 2.4.1. The two scenarios considered are Growth (Scenario B) and Deepening with Shifting to a Fleet of Larger Vessels (Scenario D). In summary, the Growth Scenario implements future vessel arrival patterns for the next 30 years which are estimated annually based on USACE (2002) report for almost all vessel types in the model. Notice that the first year in this scenario represents the current situation in the river. In Deepen with Larger Vessels Scenario, in short, on top of growth assumptions, deepening of the main channel, dredging of designated terminals in the river, and bringing reduced total number of larger

vessels for some vessel types to carry the same amount of commodity to terminals are considered. All these scenario assumptions are discussed in Sections 2.4.1.1, 2.4.1.2, and 2.4.1.3.

Each simulation run in this section has 30 replications over 30 years. In these runs, due to year-to-year growth patterns, simulation results are obtained for each year separately.

The average risks in each zone throughout 30 years can be observed in Figure 3.23 for the Growth Scenario and in Figure 3.24 for the Deepen with Larger Vessels Scenario. In these figures, the bars, representing individual years, typically exhibit increasing averages over time. These figures also provide the comparison of average risks among zones.



Figure 3.23 - Average zone risks in the Growth Scenario for 30 years



Figure 3.24 - Average zone risks in the Deepen with Larger Vessels Scenario for 30 years

Zone-based average risks and maximum risks are compared over 30 years in Figure 3.25 for the Growth Scenario and in Figure 3.26 for the Deepen with Larger Vessels Scenario. These figures depict the great difference between average risks and maximum risks observed in each zone. At the beginning in both scenarios, in zone 2, the maximum risks are around forty times higher than the average risks while they are about thirty times higher in zone 5. These high ratios could be indicators of possible disasters that may happen even though they are not expected looking at the lesser average risks.



Figure 3.25 - Zone based risks in the Growth Scenario for 30 years



Figure 3.26 - Zone based risks in the Deepen with Larger Vessels Scenario for 30 years

Average risks and maximum risks with their 95% confidence intervals, minimums, and maximums are reported for the first year and for the 30<sup>th</sup> year after they are averaged over 30 replications. The first year values are useful to understand the risk implication of deepening with shifting to a fleet of larger vessels since the effect of trade growth is not observed in the first year. Therefore, the first year results of the growth scenario (having same results with the current risks given in Section 3.6.1) represent the current risk levels in DRB and constitute a basis for the scenario comparisons. The 30<sup>th</sup> year risk estimates 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 and dredging with shifting to larger vessels.

The average risk results of the scenarios with their 95% confidence intervals for the first year and the 30<sup>th</sup> year based on 30 replications are given in Table 3.14. In this table the first year in the Growth Scenario is selected as the base case and per cent changes in the averages are compared to this base case. As seen in the table, in the Growth Scenario the average risk in zone 1 has increased around 32% at the end of the 30<sup>th</sup> year. However, in the Deepen with Larger Vessels Scenario when the first years are compared with Growth Scenario there is around 15% decrease in zone 1 average risk but around 12% and 7% increase in zone 3 and zone 4 average risks respectively. A possible reason to this is there is less need to lightering for tankers in zone 1 since the river is deeper but vessels are spending longer times at the berths to unload their cargo which is in return increasing the risks in the terminals region. When the 30<sup>th</sup> years of both scenarios are compared, zone 1

average risk is less increased whereas zone 3 average risk is increased around 26% more in the Deepen with Larger Vessels Scenario. This can be again attributed to larger vessels spending more time at the berths. These findings can be better observed for zone 1 in Figure 3.27 and for zone 4 in Figure 3.28. In these figures, the average risks for zone 1 and zone 4 are compared for the Growth versus Deepen with Larger Vessels Scenarios over 30 years.

In Table 3.15, the maximum risk results of the scenarios with their 95% confidence intervals for the first year and the 30<sup>th</sup> year based on 30 replications are displayed. In this table the changes compared to the base case (the first year in Growth Scenario) are not as notable as the changes in the average risks. Although the table shows some per cent changes in the averages, the confidence intervals are large, so that it is not possible to conclude any significance difference. As such, the 30<sup>th</sup> year of the Growth Scenario does not show significant change in the maximum risks except for zone 6. However, in the Deepen with Larger Vessels Scenario there is considerable decrease in the first year in zone 1 compared to the Growth Scenario and at the 30<sup>th</sup> year there is substantial increase in zone 3 risks compared to the first years of both scenarios.

			G	Frowth Sce	nario			Deepen with Larger Vessels Scenario				
		<u>1st Year</u> (Base)			<u>30th Year</u>			<u>1st Year</u>			<u>30th Year</u>	
ſ	Zone	Xone Average Half Widtl (95% CI	Half Width	Average	Half Width	% Change	Average	Half Width	% Change	Average	Half Width	% Change
			(95% CI)		(95% CI)	in Average		(95% CI)	in Average		(95% CI)	in Average
	1	85970	4755	113068	7875	31.52%	73234	4342	-14.81%	100677	8974	17.11%
	2	20880	458	23060	446	10.44%	21595	447	3.43%	24031	541	15.09%
	3	36874	805	43886	736	19.02%	41422	1303	12.33%	53435	2229	44.91%
	4	46977	859	52457	994	11.67%	50456	1050	7.41%	56317	1024	19.88%
	5	17950	509	20914	515	16.51%	18513	401	3.14%	21330	430	18.84%
	6	1624	54	2310	74	42.30%	1533	65	-5.56%	2261	84	39.26%

Table 3.14 - Average risks (\$) in the Growth and the Deepen with Larger Vessels Scenarios

\* Risk is defined as the sum of expected consequences expressed in dollar terms.

Table 3.15 - Maximum	isks (\$) in the Growth and the Deepen with	Larger Vessels Scenarios
		0

	Growth Scenario Deepen with Larger Vessels Scenario											
	<u>1st Year</u> (Base)			<u>30th Year</u>			<u>1st Year</u>			<b>30th Year</b>		
Zone	ne Average Half Width		Average	Half Width	% Change	Average	Half Width	% Change	Average	Half Width	% Change	
		(95% CI)		(95% CI)	in Average		(95% CI)	in Average		(95% CI)	in Average	
1	1099026	63519	1152705	67036	4.88%	980599	72316	-10.78%	1100844	60914	0.17%	
2	849703	64386	788097	49800	-7.25%	840293	59333	-1.11%	816886	42982	-3.86%	
3	910971	46904	912153	50945	0.13%	848234	46528	-6.89%	997117	63202	9.46%	
4	840641	45836	863493	48741	2.72%	823768	35931	-2.01%	847142	53888	0.77%	
5	569964	46865	563472	38136	-1.14%	571280	45217	0.23%	572542	46634	0.45%	
6	25517	5119	30406	6437	19.16%	28006	4370	9.75%	28927	6643	13.36%	

\* Risk is defined as the sum of expected consequences expressed in dollar terms.



Figure 3.27 - Average risks for Zone 1 in the Growth and the Deepen with Larger Vessels Scenarios



Figure 3.28 - Average risks for Zone 4 in the Growth and the Deepen with Larger Vessels Scenarios

In Figure 3.29, the average risks for the entire river are compared for the Growth versus Deepen with Larger Vessels scenarios over 30 years. The average risk values displayed on the figure are cumulative over all zones. The figure shows that the risks estimated in the Deepen with Larger Vessels scenario are quite comparable to the ones in the Growth scenario. This observation is complementary to the findings in Table 3.14 in regard to the risk profile shifts between zones which can also be observed in in Figure 3.27 and in Figure 3.28. Notice that, in Deepen with Larger Vessels scenario average risk in zone 1 has shifted to zone 3 and zone 4 due to the fact that tankers are spending less time in the lightering area in zone 1 yet, their holding times are increased at terminals in zone 3 and zone 4. On the other hand, Figure 3.29 shows that this shift is not generating additional risks for the entire river.



Figure 3.29 - Average risks for the Entire River in the Growth and the Deepen with Larger Vessels Scenarios

### **3.8.** A Risk Mitigation Scenario

There are several ways to mitigate risks at ports and waterways such as escorting dangerous cargo vessels, increasing pursuit distances (vessel proximity), and frequent cleanups of the river bed. There also various best practices for handling loading/unloading dangerous cargo at terminals, and best practices for lightering among many other approaches such as training, communication and interoperability to mitigate and manage risks.

In this section, a non-traditional approach to mitigate risks is considered. A risk mitigation policy that is essentially reducing the time tankers spend in terminals and lightering operations is investigated. A scenario analysis is presented on the Growth (Scenario B) and the Deepening with Shifting to a Fleet of Larger Vessels (Scenario D) scenarios that are also investigated for their impacts on risk measures in Section 3.7.

This policy requires terminals to improve their operational efficiencies and therefore reduce the time tankers spend in terminals as well as during lightering at the Big Stone Beach Anchorage in zone 1. Note that, most of the oil refineries and terminals tankers visiting reside in zone 3 and zone 4 in the river. Accordingly, here it is assumed for experimental purposes that the operational efficiency in terminals handling tankers, including lightering operations, is improved by 15% with respect to holding time. It will consequently reduce the number of vessels in the river at any point in time as shown in Figure 3.30. However, note that achieving such significant efficiency improvement may

not come easy due to various technical, safety and other regulatory issues. It is considered here to be able to show that efficiency is a way to mitigate risks.



Figure 3.30 - Average vessel density in zone 1 and zone 4 in Growth and Deepen with Larger Vessels scenarios compared to 15% efficiency

Similar to the analysis in the previous section, each simulation run has 30 replications over 30 years. Simulation results are obtained for each year separately again in these runs, due to year-to-year growth patterns. Average risks and maximum risks with their 95% confidence intervals, minimums, and maximums are reported for the first year and for the 30th year after they are averaged over 30 replications.

The results of the Growth and the Growth with 15% efficiency scenarios with their 95% confidence intervals for the first year and the 30th year are displayed for average risks on Table 3.16 and for maximum risks on Table 3.17.

In Table 3.16, the results indicate that 15% efficiency only in tanker operations can lead to about 13% decrease in average risks in zone 1 (due to efficiency in lightering operations), and around 9% and 12% risk reduction in zone 3 and zone 4 respectively (due to efficiency in terminal operations) in the first year (which also represents the current situation). The overall reduction on the average risks is about 10% for the entire river at the first year and about 12% at the 30<sup>th</sup> year.

These reductions are essentially due to observing fewer vessels at any time in the river. Efficiency in the tanker operations results in less time in the port for tankers, which are the major risk-generating entities in the system. In addition, this possibly permits other vessels to use system resources with less queue time and in turn leads to less port time for other vessels.

		Growth	n Scenario	Growth Scenario (15% Efficiency)				
	Zone	Average Half Width (95% CI)		Average	Half Width (95% CI)	% Change in Average		
	1	85970	4755	74907	1879	-12.87%		
1st Year	2	20880	458	19185	427	-8.12%		
	3	36874	805	33615	902	-8.84%		
	4	46977	859	41288	826	-12.11%		
	5	17950	509	18002	392	0.29%		
	6	1624	54	1546	60	-4.80%		
	1	113068	7875	92738	4463	-17.98%		
	2	23060	446	21538	287	-6.60%		
30th	3	43886	736	40143	1070	-8.53%		
Year	4	52457	994	46528	896	-11.30%		
	5	20914	515	21865	577	4.55%		
	6	2310	74	2298	75	-0.54%		

Table 3.16 - Average risks (\$) for zones in the Growth and the Growth with 15%

efficiency scenarios

\* Risk is defined as the sum of expected consequences expressed in dollar terms.

For the maximum risks given in Table 3.17, the risk reductions may not be that significant due to higher variation in the averages. Nevertheless, the per cent change in the averages indicate considerable reduction in the maximum risks especially for zone 1 and zone 4 for the first year as well as for the 30<sup>th</sup> year.

rowth	with	15%

		Growth	n Scenario	Growth Scenario (15% Efficiency)				
	Zone Average Half Width (95% CI)		Half Width (95% CI)	Average	Half Width (95% CI)	% Change in Average		
	1	1099026	63519	1032192	47535	-6.08%		
	2	849703	64386	813581	51490	-4.25%		
1st	3	910971	46904	868228	45714	-4.69%		
Year	4	840641	45836	797348	48187	-5.15%		
	5	569964	46865	615582	54620	8.00%		
	6	25517	5119	20773	3716	-18.59%		
	1	1152705	67036	1099206	59838	-4.64%		
	2	788097	49800	817834	48711	3.77%		
30th	3	912153	50945	926254	54594	1.55%		
Year	4	863493	48741	797016	46974	-7.70%		
	5	563472	38136	590919	42535	4.87%		
	6	30406	6437	22798	3284	-25.02%		

 Table 3.17 - Maximum risks (\$) for zones in the Growth and the Growth with 15%

efficiency scenarios

\* Risk is defined as the sum of expected consequences expressed in dollar terms.

The results of the Deepen with Larger Vessels and the Deepen with Larger Vessels with 15% efficiency scenarios with their 95% confidence intervals for the first year and the 30th year based on 30 replications are given for average risks in Table 3.18 and for maximum risks in Table 3.19.

The per cent changes in the averages shown in Table 3.18 seem even more noticeable than the ones in Growth scenarios. Through 15% efficiency in tanker operations, average risk decrease around 16% for zone 1 and 12% for zone 4 in the first year. At the  $30^{th}$  year, the average risk reduction is even more and goes up to 22% for zone 1. When the entire river is considered, the overall decrease in the average risks is about 12% at the first year and around 13% at the  $30^{th}$  year.

		Deepen Vessels	with Larger Scenario	Deepe	n with Larger Vessels Scenario (15% Efficiency)			
	Zone	Average	Average Half Width (95% CI)		Half Width (95% CI)	% Change in Average		
	1	73234	4342	61200	2117	-16.43%		
	2	21595	447	19146	535	-11.34%		
1st	3	41422	1303	36614	1228	-11.61%		
Year	4	50456	1050	44455	929	-11.89%		
	5	18513	401	19237	361	3.91%		
	6	1533	65	1565	50	2.09%		
	1	100677	8974	78400	3580	-22.13%		
	2	24031	541	21979	486	-8.54%		
30th	3	53435	2229	48294	2838	-9.62%		
Year	4	56317	1024	50569	1229	-10.21%		
	5	21330	430	21907	670	2.70%		
	6	2261	84	2326	83	2.90%		

Table 3.18 - Average risks (\$) for zones in the Deepen with Larger Vessels and theDeepen with Larger Vessels with 15% efficiency scenarios

\* Risk is defined as the sum of expected consequences expressed in dollar terms.

The change in the maximum risks for the Deepen with Larger Vessels scenarios does not seem that significant again due to large variability in the results. However, when the entire river is considered there is still about 1% and 3% decrease in the overall maximum risks at the first year and at the 30<sup>th</sup> year respectively.

		Deepen with Larger Vessels Scenario		Deepen with Larger Vessels Scenario (15% Efficiency)		
	Zone	Average	Half Width (95% CI)	Average	Half Width (95% CI)	% Change in Average
	1	980599	72316	988805	45682	0.84%
1st	2	840293	59333	813640	48637	-3.17%
	3	848234	46528	895624	57201	5.59%
Year	4	823768	35931	773413	37710	-6.11%
	5	571280	45217	575501	39226	0.74%
	6	28006	4370	24304	4701	-13.22%
	1	1100844	60914	1072939	65770	-2.53%
30th Year	2	816886	42982	770751	31555	-5.65%
	3	997117	63202	912090	61241	-8.53%
	4	847142	53888	851299	55482	0.49%
	5	572542	46634	591909	47167	3.38%
	6	28927	6643	26957	4799	-6.81%

Table 3.19 - Maximum risks (\$) for zones in the Deepen with Larger Vessels and theDeepen with Larger Vessels with 15% efficiency scenarios

\* Risk is defined as the sum of expected consequences expressed in dollar terms.

All the scenario results (for the deepening and the efficiency scenarios) obtained over 30 replication simulation runs for the average risks throughout the planning horizon of 30 years are compared in Figure 3.31 for zone 1, in Figure 3.32 for zone 4, and in Figure 3.33 for the entire river. Since zones 1 and 4 have the highest risks among all, the comparisons are performed for these zones only.

For zone 1 in Figure 3.31, Deepen with Larger Vessels Scenario has lesser average risks compared to the Growth Scenario. When 15% efficiency is implemented to the Growth Scenario, average risks are again less than Growth Scenario and they are comparable to the Deepen with Larger Vessels Scenario. Among all these scenarios, 15% efficiency

implemented in Deepen with Larger Vessels Scenario exhibits the lowest average risks in zone 1.



Figure 3.31 - Average risks for Zone 1 in Growth and Deepen with Larger Vessels scenarios compared to 15% efficiency scenarios

Figure 3.32 shows that average risks in zone 4 in Deepen with Larger Vessels Scenario result in higher risks than Growth Scenario due to longer berth holding times at terminals. However, the figure demonstrates 15% efficiency decreases risks in both scenarios.



Figure 3.32 - Average risks for Zone 4 in Growth and Deepen with Larger Vessels scenarios compared to 15% efficiency scenarios

In Figure 3.33, the average risks over 30 years are compared for the entire river. That is, the risk values are accumulated over all zones. This perspective is of interest due to the risk profile shifts among zone 1 and other zones. The figure shows that, 15% efficiency cases generate lesser risks for the entire river for both scenarios. On the other hand, for the 15% efficiency cases, Deepen with Larger Vessels Scenario has slightly lower risks than the Growth Scenario.



Figure 3.33 - Average risks for the Entire River in Growth and Deepen with Larger Vessels scenarios compared to 15% efficiency scenarios

As a summary, the Deepen with Larger Vessels Scenario leads to lesser number of vessels do lightering (even if each vessel lighters more) and lesser number of vessels wait due to tide in zone 1. This causes lesser vessel density in zone 1 and decreases average risks. In return, since the cargo is not lightered and carried to terminals with large vessels, this causes longer berth holding times and increases average risks in zones 3 and 4. Through implementation of 15% efficiency in lightering and terminal operations for tankers, vessel density is reduced in zones tankers have activity. This helps to reduce risks significantly, specifically in zones 1, 3 and 4 in both the Growth, and the Deepen with Larger Vessels scenarios. All these effects remain consistent throughout the 30-year planning horizon.

## **3.9.** Conclusion on Risk Analysis

This chapter discusses and uses a simulation model for risk assessment of vessel traffic to study potential incidents that would result in dire consequences in Delaware River as well as in the region. The formulation considers the causal chain of events with all possible instigators, accidents and consequences. It uses the probabilities and expected consequences to evaluate risks over many situations, time and geography. In addition, the simulation model, in which the risk model is incorporated, is instrumental in estimating key parameters essential to risk computations.

A particular risk measure that is the sum of the expected consequences of various potential incidents is used in the analysis to quantify the risks in DRB. The approach is such that the mathematical risk model associates a risk value with every possible situation generated by the simulation model. Repeating this procedure over time and geography, a risk profile is obtained to show dynamic maritime risks in each of the six zones over a year.

In this study, average risk and maximum risk statistics are used to produce the risk profiles. Average risks are important to evaluate how risky situations compare. Maximum risks in the risk profile are typical disaster indices providing valuable information for risk-reduction considerations. In essence, maximum risk expresses a possibility more than likeliness. The results for the current situation in the river have suggested that the greatest risks are at the Breakwater entrance and the lightering area (zones 1), and the region between Wilmington (DE) to Eagle Point (NJ) where most of the oil terminals reside (zones 3 and 4) compared to the rest of the river. This is mainly due to tanker and crude handling operations including lightering in Big Stone Beach Anchorage, and loading and unloading operations in terminals upstream. Accordingly, oils spill and grounding accidents are generating the most severe consequences, while environmental damage is the most hazardous consequence. This finding is in line with the oil spill disasters in the past decades in Delaware River. The results also indicate Chesapeake and Delaware Canal entrance is a dangerous intersection for the moving vessels due to high moving vessel density.

In addition to the current situation, risk profiles based on potential future projections for Delaware River were also considered. The scenarios presented in Chapter 2 are used to analyze the effects of trade growth, deepening and shifting to a fleet of larger vessels in the river on the risk measures. The results show that, trade growth causes about 22% increase on the average risks for the entire river in 30 years while the major increase is about 32% at the entrance and the lightering area. The deepening together with its potential effect of shifting to a fleet of larger vessels at the port is causing a risk profile change for the entire river. Due to reduced lightering need of tankers, risks at the main entrance would shift to the terminals area where tankers are going to spend more time because of increased amount of cargo loading/unloading operations. However, when the

entire river is considered the overall risks are around the same for the both cases in the beginning years as well as at the end of the planning horizon of 30 years.

Providing a risk profile of the entire river through such a model assists producing and testing several risk mitigation policies. In this study, in order to mitigate risks, a rather non-traditional approach in large scale is sought after through increasing operational efficiency. One way to achieve that is to improve terminal efficiencies resulting in shorter berth holding times, which will release vessels out of terminals faster, and therefore resulting in a lesser number of vessels at any point in time in the river. A demonstration of this idea achieved using the model developed, through the scenarios including trade growth and deepening assumptions over the 30 years planning period. The results show that a 15% increase in operational efficiency can lead to around 10% to 12% average risk reductions for the entire river. This decrease could be up to 22% at the entrance zone and up to 12% at the terminals region. Even though achieving such efficiencies might be quite challenging due to many reasons such as financial, physical and regulatory limitations, any concerted effort among terminals in the river towards better efficiencies may result in considerable risk reductions coupled with environmental benefits.

Effects of situational attributes on the risk values are not analyzed in this study. Basically, these effects are obtained through expert judgment elicitation and directly used in the risk calculations in the simulation runs. Some of these effects blend with others, and revealing individual effects require further analysis.

The risk assessment model developed in this chapter has several simplifications and assumptions. Although similar events and situations are used in studies in literature, the model framework, the probabilities estimated and the consequence impact levels all rely on the historical accident data. An important challenge is the analysis of consequence impact levels to which the risk evaluations are very sensitive. This type of a study requires thorough analysis of consequence impact levels depending on situational attributes and accident types. Unfortunately, the historical data used in this study are not detailed enough to reveal all possible interactions. In this regard, especially in order to elaborate on the particular effects of situations, some of the modeling assumptions and data analysis parts can be improved.

Other studies address uncertainties inherent in risk assessment associated with data issues, biased expert judgments, modeling simplifications or others (Winkler, 1996; Nilsen and Aven, 2003). Fowler and Sorgard (2000) defined major uncertainty categories as traffic data and historical statistics, models for calculation of critical situations, and accident probabilities. Consequently, the benefit of risk assessment studies are mostly due to revealing complex relations of several system components, identification of unusual situations and patterns in the system, and understanding effectiveness of risk mitigation measures rather than the precision of results.

An improvement direction for a future research can be inclusion of other possible factors influencing the occurrence of instigators, accidents and consequences. Vessel reliability looking into vessel age, flag of a vessel, and experience of the crew is one of the most important of these factors. Another important factor can be local traffic density to include recreational motorboats, touristic boats, fishing vessels and local ferries. Although they were not important factors for this study, wind and visibility conditions are very important for other ports and waterways. On the other hand, in order to perform other policy analysis vessel pursuit distance can also be implemented, and accordingly the effects of possible traffic scheme policies on risks can be tested. However, inclusion of any of these factors requires implementation of each process and/or data in the simulation model, and needs particular modeling effort.

# 4. VESSEL PRIORITIZATION

Delaware River is a major port of entry for energy commodities, such as crude oil (petroleum), and liquefied petroleum gas (LPG) and other important commodities such as chemicals, food products, cars, steel coils and many others essential to the U.S. economy. The U.S. national economy is highly dependent on imported energy products, which are shipped from overseas in tankers. According to U.S. Energy Information Administration, in 2011, about 45% of the petroleum and about 8% of the natural gas consumed in the U.S. relies on imports. Daily maritime-based imports of crude oil averaged about 8.5 million barrels, or equivalently four super tankers a day (Short-Term Energy Outlook, August 2012; U.S. Natural Gas Imports & Exports 2011). A global supply chain moves energy commodities to the U.S. from sources over international routes, and unloading at petrochemical port facilities. Delaware River houses a number of oil/petroleum terminals (e.g., Fort Mifflin (PA), Marcus Hook (PA), Valero Paulsboro (NJ), Conoco Philips (PA), Delaware City (DE) Wilmington Oil Pier (DE)).

Maritime trade in Delaware River and Bay (DRB) is through operations at river terminals. In 2005, the Delaware River major ports' annual import tonnage was 57 million short tons and \$41 billion in value (Maritime Commerce in Greater Philadelphia, 2008). Any port closure hinders the flow of cargo in and out of the port and needs to be rapidly resolved. The incident may be safety related or security related but the common understanding is the response to an incident must not unreasonably affect the free flow of goods, while simultaneously reducing risk to an acceptable level.

Based on the SAFE Port Act, (P.L. 109-347) the Secretary of Homeland Security prepared a strategic plan to enhance the security of the international supply chain (DHS, 2007). This plan focuses on resumption of trade following an incident at the ports and contains protocols for prioritization of vessels and cargo. In the plan, a multi-agent structure is outlined for how goods should be prioritized in coordination with federal, state, private sector, and international stakeholders.

This chapter considers the resumption of trade, which is the final stage of recovery from an incident. Resiliency is dependent on how fast the port recovers. DHS's (2007) report identifies vessel prioritization as a critical part of risk management approach to incident response, and the main goal is to achieve an optimum balance between the security and/or safety measures, and the recovery of transportation capabilities. Using the simulation based risk model developed, the chapter focuses on vessel prioritization rules that can be used for entry into and exit from the river during recovery operations, and evaluates their impact on port performance as well as risk performance.

An incident similar to Athos I oil spill is considered to create a hypothetical closure in the river. Three scenarios are prepared resulting in varying degrees of impact on traffic as well as the environment. In two of these scenarios, the river is closed to vessel traffic due to a major oil spill and cleanup process takes three days before the vessels are permitted in the river. In another scenario, there is a medium environmental event caused by an accident, and the river is partially closed to vessel traffic for two days. In all these

scenarios, several vessel sequencing rules are tested and their impacts on port and risk performance measures are investigated.

# 4.1. Literature Review

While vessel prioritization is considered an important issue in port and waterway management, the literature is limited. In fact, to the best of our knowledge, no directly related published work exists in this area. In this section, some prior work in disaster recovery that is related to our interest in this study is reviewed below.

Altay and Green (2006) present a review of the Operations Research and the Management Sciences literature on disaster operations management. The authors indicate that typical recovery activities include debris cleanup, financial assistance to individuals and organizations, rebuilding of roads, bridges and key facilities, sustained mass care for displaced human and animal populations and full restoration of lifeline services, among others.

DeBlasio (2004) presents a case study of four U.S. disasters and actions taken to mitigate them in the days after the disasters. It highlights advance preparation, technical communication systems usable during the incident, advanced Intelligent Transportation Systems (ITS) facilities and traffic management centers, and systems that are redundant and resilient. Bryson et al. (2002) proposed mathematical modeling techniques for disaster recovery planning based on arguments of feasibility, completeness, consistency, and reliability. An example was a mixed integer linear programming model to select the best disaster recovery plan under limited resources.

Ham et al. (2005) discusses reconstruction of interregional commodity flow over a transportation network after a major earthquake. They have incorporated regional input–output relationships, and the transportation network flows to assess the economic impacts of such an unexpected event.

Lee and Kim (2007) propose strategies for post-event reconstruction to minimize time of recovery and economic loss. They proposed a model to minimize total time for recovery calibrated to favor shorter recovery even at greater economic loss. Selection of optimal recovery strategies is done via a genetic algorithm and simulated for use over bridges in the Chicago area.

Friedman et al. (2006) introduce DIETT<sup>5</sup> which provides a means to adapt Microsoft Access, and Excel for use in evaluating transportation choke points (TCP's) in a regional or state setting. The value of this electronic product rests in the adapted algorithms allowing a user to enter data about their transportation network, and be provided with a relative risk of TCP's for further evaluation, and for use in traffic planning situations for emergency purposes.

<sup>&</sup>lt;sup>5</sup> Disruption Impact Estimating Tool-Transportation (DIETT): A Tool for Prioritizing High-Value Transportation Choke Points

# 4.2. Prioritization for Resumption of Trade

The objective in vessel prioritization is to identify products that the region has immediate needs and deliver them on a timely manner. Every shipper's products are important but some have urgency over others, such as heating oil in winter or food products at any time have more urgency, when compared to TV sets or music players.

DHS (2007) strategy points out importance of coordinating between local stakeholders and federal agencies such as U.S. Coast Guard (USCG), the Customs and Border Protection (CBP), and the Transportation Security Administration (TSA) to determine cargo priorities through a local decision making process. The strategy defines primary factors to be considered for local prioritization based on safety, security and commodity. These factors are listed below.

- The security status of the vessel,
- The ability of vessels to move to and from its berth,
- The capacity of the port infrastructure to offload the cargo and move it from the port,
- Commodity needs at the national, regional and local level,
- The need for the vessel to move cargo out of the port.

National commodity priorities include, but are not exclusively as foloows:

- Emergency Needs: Materials necessary for the saving lives such as supplies for medical response, restoration of power, and potable water.
- Response Needs: Personnel and equipment essential to carry out response operations at the incident site such as fire boats.
- Commodity Needs: Goods that may be in immediate shortage such as crude oil, heating oil and chemicals necessary for industrial continuity, and drinking water.
- National Security: Cargo necessary for national security concerns such as small vessels to conduct escort duties.

In order to assist in prioritizing cargo, the DHS (2007) report provides a decision tree which includes relevant logistical, priority and security factors. On the other hand, the decision tree does not assign a fixed value to each factor, and recommends responders develop appropriate scoring system to weight the factors depending on port specific conditions. Although the DHS (2007) strategy suggests a multi-agency command structure for setting priorities, the actual process of prioritization is very complicated due to interaction of many factors and variables.

Assuming that vessel security and safety issues are handled by the USCG and other agencies, in this chapter, the focus is on the issues regarding sequencing of vessels and decisions regarding the direction of the flow (inbound or outbound) to resume trade.

When the river is closed for trade, possibly due to unexpected and sudden nature of the incident, there will be accumulation of incoming vessels at the entrance of the river.
These vessels will be in random order by their type according to their arrival time. There might be possible sequencing policies such as first-come-first-served, most needed items first, least risky vessels first or least service time vessels first (to minimize the total accumulation faster). This is a scheduling problem in essence. However, when the risks are involved, the problem gets complicated and it becomes a multi-objective decision problem.

There are multiple goals of this process, such as minimizing safety/security risks, minimizing economic impacts, and many others. Thus, the entire problem is very complicated and requires many assumptions even for simple analytical solutions or approximations. Accordingly, in this chapter the issue of port reopening and vessel prioritization is studied through scenario analysis based on a hypothetical incident generated in the simulation environment.

There are two general sequencing policies adopted. The first one is giving priority to some of the vessels and the other one is permitting vessels in the river on a first-come-first-served basis. On the other hand, in order to control the flow and proximity of vessels entering the river, there should be a minimum distance between two consecutive vessels. This can be called pursuit distance between vessels. Two different pursuit distance policies are employed in this manner as explained in incident scenarios. Below, the case of Athos I which was a grounding resulting in a major oil spill in DRB is briefly reviewed. Then, the scenarios considered are provided.

### 4.3. The Case of Athos I in 2004

On Friday, November 26, 2004, at approximately 9:15 p.m., the 750-foot, single-hull tanker Athos I, registered under the flag of Cyprus, was reported to be leaking oil into the Delaware River en route to its terminal at the Citgo asphalt refinery in Paulsboro, New Jersey. It had two punctures in its hull (University of Delaware Sea Grant Program, 2004).

On January 18, 2005, the Coast Guard released photographs of an anchor that has been removed from the Delaware River for analysis as part of their continuing investigation into the spill incident. The anchor and an 8-by-4-foot slab of concrete were found in the tanker's path to the refinery dock. Approximately 265,000 gallons of oil spilled into the Delaware River from the T/S Athos I.

The spill impacted approximately 115 miles of shoreline along the tidal portion of the Delaware River, from the Tacony-Palmyra Bridge, which links northeast Philadelphia to Palmyra, New Jersey, south to the Smyrna River in Delaware. In response to the initial threat, Public Service Enterprise Group (PSEG) temporarily closed two reactors at the Salem Nuclear Power Plant along the river at Artificial Island, New Jersey. After a three-day shutdown of the Port of Philadelphia immediately after the spill, commercial vessels were allowed back into the port, but were required to undergo a decontamination process prior to leaving the affected area.

# 4.4. Incident Scenarios Considered for Investigation

In this chapter, an incident is considered to take place in Paulsboro blocking the traffic in the main channel. The incident is similar to the case of Athos I, described earlier. Figure 4.1 shows a screenshot from the simulation model at the incident location after reopening. Three cases are prepared, two with a major oil spill and cleanup effort (Cases A and B) and the other with medium level environmental consequence (Case C). The duration of the closure is assumed to be 3 days for Cases A and B (as was the case of Athos I incident) and 2 days for Case C.



Figure 4.1 - An Arena simulation model screenshot showing the hypothetical incident location at Paulsboro after reopening

Case A involves a major oil spill with a potential of spreading to other parts of the channel and therefore restricts vessel movements in the river. Case B is a variation of Case A such that it delays the inbound vessels up to a certain time before they start moving in. Case C, on the other hand, while keeping the channel closed, still allows vessel movements in the southern points of the incident. This will allow vessels to go from one terminal to another in the southern part of the channel without crossing the blockage point. Thus, Cases A and B nearly put the channel into a state of freeze until the incident is cleared, while Case C retains some flexibility in vessel movements. In all cases, resumption of flow is achieved based on a prioritization mechanism which is the focus of this chapter.

Vessel prioritization has a direct impact on vessel waiting times to enter the channel and port times. In all cases employing prioritization, tankers and reefer vessels carrying food products are given higher priority over other vessels. Below each case is discussed in detail.

#### Case A - Major Consequence Channel Closure:

This case involves a major spill with a potential of spreading to other parts of the channel and therefore vessel movements in the river are restricted. Vessels that are already on the move either south or north of the spillage point when it occurs are asked to anchor at the closest location possible. Loading/unloading operations at terminals continue unaffected; however the vessels that are ready to leave will not be permitted to do so until the incident is completely cleared. Also, no new vessels are allowed to enter the channel until the incident is over. Once the incident is over, vessels already in the river continue their navigation. Vessels at terminals are allowed to leave. Inbound flow of vessels are based on a prioritization mechanism.

#### *Case B - Major Consequence Channel Closure with Delay in Inbound Flow:*

Case B is a variation of Case A where the inbound vessels are delayed up to a point in time which may be determined by the number of vessels remaining in the river (e.g., inbound flow starts when there are a total of 10 vessels in the river) or by a time threshold (e.g., inbound flow starts in 5 hours after the incident is cleared). Thus in this case, the inbound flow starts after some delay giving the system a chance to release some outgoing vessels before the inbound flow starts.

#### Case C - Medium Consequence Channel Closure:

This case, while keeping the channel closed, still allows vessel movements in the southern points of the incident. This will allow vessels to go from one terminal to another in the southern part without crossing the blockage point. This is a common practice in such incidents and geographies if the incident does not pose a threat to operations in major parts of the waterway and yet keeps the channel closed. Vessel entrances to and departures from terminals south of the blockage are done in a normal manner at any point in time. Once the incident is cleared, vessels in the northern part of the incident continue their movements from the point of interruption. New arrivals destined to northern points are allowed to move upriver based on a prioritization mechanism.

Vessel handling during and after the incident is as follows. Vessels arriving during the incident are placed into a queue at both entrances, referred to as closure queues. Even after the incident is cleared, new arrivals are placed into these queues as long as there are vessels in them. After the incident is cleared, vessels from closure queues proceed to the river in a sequence arranged according to a priority and a vessel pursuit distance. In prioritizing vessels in closure queues, higher priorities are given to tankers and refrigerated vessels considering the commodity needs and the need for the vessel to move cargo. Also, 15 minute and 45 minute pursuit distances are evaluated to better understand the impact of pursuit distance on performance and risk behaviors. Clearly, both priority and the pursuit distance have an impact on the vessel waiting time in the queue.

In all these cases, we have focused on how fast the system returns to normal after the incident is cleared. Here, it is proposed to define "Time to Return to Normal" as the time from the incident occurrence to the point in time when there is no vessel left in the queue. This is probably the most important measure in planning for disaster preparedness scenarios and exercises. From this point on no arriving vessel is put in this queue and normal operations resume. Various types of information about the queue such as waiting times and numbers of vessels waiting are obtained from the simulation model.

Note that there is the risk component in managing the vessel queue. As soon as the incident is cleared, there will be a number of vessels moving into the river and clearly there will be increased vulnerability to accidents with potentially high consequences. Mitigating these risks during the recovery process is a major challenge, and both priority

and pursuit distance have impact on the resulting risks. Experiments in the following section are designed to shed some light on the performance and risk issues surrounding the priority queue in entering the river.

### **4.5.** Experiments with the Model of DRB

In this section, various experiments carried out with the traffic simulation model are introduced and the results are discussed. The experiments centered on the impact of priority (PR) and pursuit distance (PD) on time to normal, waiting times, and risk outcomes of the recovery process.

The incident is set on November 1st (the 305<sup>th</sup> day of the year) with a duration of 3 days in Cases A and B and 2 days in Case C. The model is run for 1 year with 100 replications to create a reasonable sample size to make reliable estimations.

In each case, performances of the following policies are tested in numerical experimentation.

- First-In-First-Out (FIFO) service in closure queues with 15-minute pursuit distance in BW entrance,
- First-In-First-Out (FIFO) service in closure queues with 45-minute pursuit distance in BW entrance,
- Priority service in closure queues with 15-minute pursuit distance in BW entrance,

• Priority service in closure queues with 45-minute pursuit distance in BW entrance.

Closure queue performance is expressed using the following measures:

- *Closure queue clearance time* is the time to clear closure queues from the point in time the first vessel is picked up from the queue until the time when no vessel remains in the queues.
- *Time to normal* is the time the incident starts until the time when no vessel remains in the queues.
- *Cumulative waiting time* is the total time of all the vessels visiting closure queues.
- *Total number of vessels in queue* is the total number of vessels visiting closure queues.
- *All vessels waiting time* is the average waiting time over all vessels visiting closure queues.
- *Tankers waiting time* is the average waiting time of all tankers visiting closure queues.
- *Refrigerated vessels waiting time* is the average waiting time of all refrigerated vessels visiting closure queues.
- *Other vessels waiting time* is the average waiting time of all vessels other than tankers and refrigerated vessels visiting closure queues.

### **4.6.** Performance Implications of Vessel Prioritization

Table 4.1 and Table 4.2 provide a comprehensive summary of the results for priority and pursuit distance policies in all cases showing results for key performance measures regarding closure queues.

In Case A, Table 4.2 shows both Priority and FIFO service disciplines affect all measures equally, except that tankers and refrigerated vessels waiting times are shorter when they are given a priority. As expected, the average waiting time is the only measure that changes when comparing FIFO against Priority discipline. Waiting times of other vessels are slightly longer in the Priority scenario. Table 4.1 shows the pursuit distance of 15-minute results in around 8 hours of closure queue clearance time while the extended 45-minute pursuit distance produces a 30 hours clearing time.

In Case B, due to the delay until 10 vessels remain in the system to permit waiting vessels to enter the river, longer queue clearance times, longer times to normal (resulting in higher number of vessels in the closure queue) and longer waiting times are produced when compared to Case A.

The reason for tanker waiting times being shorter in the 45-minute (as opposed to 15minute) pursuit distance Priority scenario (also true for Case A) is that the tankers arriving after the incident is over and still visiting the closure queue have much shorter waiting times compared to the ones already in the system during the incident. This reduces the average waiting times in the Priority case.

		Closure Queue		Total	Time	Cumulativ	e Waiting	Total No of Vesssels	
		Clearance Time (hrs.)		to Normal (hrs.)		Time (hrs.)		in Queue	
		Avarago	Half Width	Auorogo	Half Width	Avarago	Half Width	Avorago	Half Width
		Average	(95% CI)	Average	(95% CI)	Average	(95% CI)	Average	(95% CI)
	FIFO (PD: 15min)	8.2	0.35	80.5	0.35	1299.2	63.93	36	1.49
Case A - Complete	Priority (PD: 15min)	8.2	0.40	80.5	0.40	1257.4	65.18	35	1.60
Closure	FIFO (PD: 45min)	30.1	1.66	102.3	1.66	1564.5	90.44	43	2.31
	Priority (PD: 45min)	30.8	1.47	103.0	1.47	1564.6	88.63	44	2.02
Case B Complete	FIFO (PD: 15min)	10.9	0.53	108.6	4.38	2374.8	217.17	47	2.29
Closure with	Priority (PD: 15min)	11.2	0.66	114.8	5.72	2582.8	326.37	48	2.88
Inbound Delay	FIFO (PD: 45min)	44.2	2.78	146.0	7.14	3344.3	362.28	63	3.91
	Priority (PD: 45min)	42.8	2.65	143.8	7.05	3163.8	346.00	61	3.75
	FIFO (PD: 15min)	2.8	0.19	51.1	0.19	279.9	20.30	12	0.76
Case C - Partial	Priority (PD: 15min)	2.7	0.19	51.0	0.19	269.6	21.05	11	0.76
Closure	FIFO (PD: 45min)	9.0	0.58	57.3	0.58	290.2	24.78	12	0.78
	Priority (PD: 45min)	9.3	0.73	57.6	0.73	303.8	27.99	13	0.99

Table 4.1 - River closure scenarios and reopening results on overall port performance

	-	Tankers -		Refrigerate	d Vessels -	Other V	essels -	<b>Overall Vessels</b> -	
	_	Waiting Time (hrs.)		Waiting Time (hrs.)		Waiting Time (hrs.)		Waiting Time (hrs.)	
		Avanaga	Half Width	Average	Half Width	Avanaga	Half Width	Augrogo	Half Width
		Average	(95% CI)	Average	(95% CI)	Average	(95% CI)	Average	(95% CI)
	FIFO (PD: 15min)	36.7	1.61	35.3	2.89	36.1	1.05	36.4	0.89
Case A - Complete	Priority (PD: 15min)	33.3	1.40	31.9	3.07	36.5	1.12	35.5	0.93
Closure	FIFO (PD: 45min)	37.5	1.45	36.8	2.87	35.7	1.03	36.4	0.96
	Priority (PD: 45min)	27.6	1.50	31.4	3.91	38.6	1.43	35.3	1.01
Casa B. Complete	FIFO (PD: 15min)	49.5	2.57	48.0	4.02	48.9	2.48	49.1	2.31
Closura with	Priority (PD: 15min)	47.2	2.99	47.2	4.34	52.8	2.92	50.7	2.69
Inbound Delay	FIFO (PD: 45min)	51.1	2.83	51.5	3.41	49.7	2.68	50.3	2.58
	Priority (PD: 45min)	38.1	2.21	45.9	4.34	54.4	2.84	49.5	2.37
	FIFO (PD: 15min)	24.1	2.20	15.4	2.72	25.0	1.29	24.3	0.99
Case C - Partial Closure	Priority (PD: 15min)	22.3	1.97	15.3	2.97	25.1	1.33	24.3	0.96
	FIFO (PD: 45min)	22.1	1.76	15.0	2.78	24.0	1.27	23.5	0.98
	Priority (PD: 45min)	19.3	2.02	19.5	3.26	24.9	1.48	23.6	1.11

Table 4.2 - River closure scenarios and reopening results on vessel waiting times

Prioritizing tankers and refrigerated vessels again result in shorter waiting times when comparing Priority and FIFO scenarios in each of 15-minute and 45-minute pursuit distances. Overall vessels waiting times and times to normal tend to remain unchanged in each of the Priority and FIFO scenarios.

Case C is the closest to no-incident or normal operation scenario, and therefore all the performance measures are much smaller than their counterparts in Cases A and B. In particular, there are much smaller numbers of vessels in closure queues, and therefore Priority or FIFO scenarios do not change in their behaviors.

Thus, conclusions from Table 4.1 and Table 4.2 include Case C is the most desirable among all cases with minimum waiting times, queue clearance times as well as times to normal. Thus, considering only the port performance the channel may operate like the one in Case C in the case of an incident. This is the best performing operation. Case A is the next choice based on time to normal and clearing times. If it is a necessity, Case B may be chosen provided that it offers some other benefits not considered here. Whatever case is selected, prioritizing tankers and refrigerated vessels over using the FIFO discipline in closure queues is beneficial with respect to waiting time measures while keeping time to normal unchanged. The Priority scenario will perform even better for the prioritized vessels in scenarios with longer pursuit distances. The choice of the pursuit distance whether it is 15 minutes or 45 minutes (or some other interval) should be based on another measure such as risk, which is discussed later in this chapter.

The behavior of the number vessels in the river and at the entrance queue around the time of the incident and thereafter provides a better understanding of overall system reaction. Figure 4.2 shows the number of vessels in the river and in the closure queue between days 300 and 320 in Case A. The incident occurs right before 440,000<sup>th</sup> minute (day 305) in the run and the number of vessels in the system remains the same until the incident is over at around 444,000<sup>th</sup> minute (within the day 308) at which point vessels start moving into the river. As can be seen, the number in the closure queue keeps increasing during the closure and rapidly zeros itself after the incident, increasing the number of vessels in the river in all three scenarios. Both of the 15-minute scenarios rapidly increase the number in the river almost in the same manner, as expected, while the 45-minute scenario gives a chance to the system to release some vessels and build slowly. In the remaining time all three scenarios seem to be quite comparable.



Figure 4.2 - Number of vessels in the river and in the closure queue between days 300 and 320 in Case A (Full Closure)

Figure 4.3 shows a similar behavior except that river opens with a delay and vessels keep accumulating in the closure queue up to the point of reopening after which the number in the queue rapidly drops to zero increasing the number in the river. Again, the 15-minute scenarios build vessels in the system rapidly as compared to 45-minute scenario and the behavior after that is quite similar to Case A.



Figure 4.3 - Number of vessels in the river and in the closure queue between days 300 and 320 in Case B (Full Closure with Inbound Delay)

Figure 4.4 shows again a similar behavior except that accumulation in the closure queue is not much due to the fact that the operation at the south of the incident is close to normal conditions. After reopening, the number in the closure queue rapidly drops to zero slightly increasing the number in the river. The three cases here exhibit a very similar behavior and operate close to normal conditions.



Figure 4.4 - Number of vessels in the river and in the closure queue between days 300 and 320 in Case C (Partial Closure)

Figure 4.5 shows vessel port times and the number of vessels in the river between days 308 and 310 in Case A. Vessel port times are slightly higher in the 45-minute scenario after the incident is over and this behavior continues after a while until the system returns to normal operation. The buildup in the 15-minute scenario is clear in the number of vessels in the system.



Figure 4.5 - Vessel port times and number of vessels in the river between days 308 and 310 in Case A (Full Closure)

In Case B, as Figure 4.6 indicates, the port times are dominated by the 45-minute scenario and the number in the queue is dominated by the 15-minute scenario. Again, there should be added benefits to work with this case in reopening ports.

Case C, in Figure 4.7, shows a behavior very similar to operation under normal conditions. Both port times and the number of vessels in the closure queue show very similar behaviors under the two Priority scenarios. Again, clearly this is the most preferable case in reopening ports for resumption of trade.



Figure 4.6 - Vessel port times and number of vessels in the river between days 308 and 310 in Case B (Full Closure with Inbound Delay)



Figure 4.7 - Vessel port times and number of vessels in the river between days 308 and 310 in Case C (Partial Closure)

## 4.7. Risk Implications of Vessel Prioritization

In this section, the risk implications of Cases A through C with service discipline and pursuit distance scenarios are investigated, and risks resulting from policies used to manage closure queues are discussed. Safety risks at the entrance in zone 1 and at the terminals region in zone 4 are used to compare each case and scenarios.

The results are based on 1 year simulation runs over 100 replications. In these scenarios since the focus is on instantaneous risks within a small period of time, that is a couple of days period after reopening, instantaneous risks are averaged over 100 replications for each time point a risk observation is made. Thus, average instantaneous risk values are reported in figures and regarded as instantaneous risks for simplicity. In addition, these instantaneous risk values are averaged for the period after reopening until day 320, and the average risks for this period are reported in tables with their standard deviation, 95% confidence interval (half-width), and the maximum instantaneous risk observation during this period.

Maximum instantaneous risks reported for the period in scope indicate the severity of situations that can be observed in the scenarios, and possibly is a key indicator of the risk performance of the scenarios in this section. Average risks consider the period of complete recovery and give a general measure of risk performance of the scenario (which can also be compared to actual current risks in the system). Standard deviation of instantaneous risks within the recovery period is another measure indicating the variability of risks during this period.

Figure 4.8 displays average risks of the four pursuit distance scenarios for Case A in zone 1. The spike in risks (maximum instantaneous risk) is clearly visible after the closure queue opens up on day 308. After this point, the rupture in the risk spectrum can easily be seen indicating a shift to a higher risk band.

On the other hand, Table 4.3 shows average risks obtained after day 308 up to day 320 which appears to be the time the system behavior returns to normal. In the table, the Priority (15 min.) scenario is responsible for the highest maximum instantaneous risk followed by the FIFO (15 min.) scenario. This is due to allowing tankers in the river in every 15 minutes in the Priority scenario. The FIFO (45 min.) scenario is creating the lowest maximum risk for Case A.

In the twelve days after reopening, the Priority (45 min.) scenario produces greater average risk but lesser variation compared to the Priority (15 min.) scenario. In the Priority (45 min.) scenario, since the queue clearance time is longer due to longer pursuit distance of vessels, greater average risk is possibly due to accumulation of more tankers and their prioritization to the front of the queue. That is, 45-minute pursuit distance brings tankers closer to each other into the system between days 308 and 320. This also affects when the first stream of tankers is leaving the system, they come across with a second stream of tankers. Therefore, all these effects increase the average risks. The 15minute pursuit distance on the other hand serves the closure queue faster, and lets the remaining tankers move into the system as they arrive. This produces much higher risks at the beginning but reduces them later in the same time frame up to day 320.



Figure 4.8 - Zone 1 instantaneous risks between days 300 and 320 in Case A (Full Closure)

Table 4.3 - Zone 1 average risks within the period between days 308 and 320 in Case A

(Full Closure)	(Full	Closure	)
----------------	-------	---------	---

Scenario	Average Risk	Maximum Risk	Standard De viation	Half Width (95% CI)
Priority (15min)	115801	341308	30285	3482
Priority (45min)	124291	222211	22284	2562
FIFO (15min)	124887	262532	23614	2715
FIFO (45min)	118674	214447	22497	2587

\* Risk is defined as the sum of expected consequences expressed in dollar terms.

Figure 4.9 shows risks of the four pursuit distance scenarios for Case B in zone 1. In this figure, high risk spikes cannot be observed due to the extra delay employed to inbound vessels in Case B permitting the vessels in the river to leave the system. Thus, inbound vessels and outbound vessels do not come across and do not generate higher risks. For instance, even the Priority (15 min.) scenario is generating almost half of the maximum risk compared to Case A. In addition, around day 308, instantaneous risks are even lower than the average risks since the vessels entering the river find an empty system.

The average risks with their standard deviation and 95% confidence interval, and the maximum instantaneous risks between days 308 and 320 in zone 1 are given in Table 4.4. In the twelve days after reopening, the risks of the Priority (15 min.) scenario appear to dominate the others producing highest risks. This is due to the fact that more tankers accumulate in queues due to the delay in reopening and they are released into the river with 15-minute intervals. This generates more tankers in the system when compared to the FIFO or the 45-minute pursuit distance scenarios. The FIFO (45 min.) scenario produced the lowest risks in Case B. However, since the system is almost empty when vessels start to enter the river, the FIFO (15 min.) and the FIFO (45 min.) scenarios produce very similar results.

When the average risks of Case B are compared to Case A, the Priority scenarios have almost similar average risk results while the FIFO scenarios in Case B produce a little lower average risks.



Figure 4.9 - Zone 1 instantaneous risks between days 300 and 320 in Case B (Full Closure and Delay in Inbound)

Table 4.4 - Zone 1 average risks within the period between days 308 and 320 in Case B (Full Closure and Delay in Inbound)

Scenario	Average Risk	Maximum Risk	Standard Deviation	Half Width (95% CI)
Priority (15min)	125349	189626	22649	2604
Priority (45min)	123969	177079	22860	2628
FIFO (15min)	111039	168259	21368	2457
FIFO (45min)	110751	167295	24682	2838

\* Risk is defined as the sum of expected consequences expressed in dollar terms.

Figure 4.10 and Table 4.5 show risks in zone 1 with the four pursuit distance scenarios for Case C. The risks behave similarly to the ones in Case A in generating a risk spike at the reopening. However, the distribution of instantaneous risks after the reopening is

much lower since the system is already partially operating during closure permitting some of the vessels leave the system. This decreases the chances of interactions with incoming vessels and reducing the risks.

Table 4.5 indicates the Priority (15 min.) scenario is producing the highest maximum instantaneous risk while the FIFO (45 min.) scenario has the lowest one. On the other hand, average risks are similar to each other in all scenarios while the Priority (45 min.) scenario having the highest average risk, possibly due to accumulation of more tankers during longer queue clearance time.

The maximum instantaneous risks produced in Case C are lower than the ones in Case A but in most scenarios they are still higher than the ones in Case B as evidenced in Table 4.3 through Table 4.5. However, notice that the FIFO (45 min.) scenario in Case C is the least risk generating among all scenarios in terms of average as well as maximum risks.

Case B produces lower maximum instantaneous risks due to the fact that the system is already cleared (until 10 vessels remain in the system) when the closure queue opens up. On the other hand, average risks produced in Case C are lower than other two cases. This is mainly due to Case C is permitting partial operation of the system. In that sense, Case C is the least risk producing case among the three cases, and therefore the more desired case to operate under, as it is also concluded in the performance implications discussion.



Figure 4.10 - Zone 1 instantaneous risks between days 300 and 320 in Case C (Partial Closure)

Table 4.5 - Zone 1 average risks within the period between days 307 and 320 in Case C (Partial Closure)

Scenario	Average Risk	Maximum Risk	Standard Deviation	Half Width (95% CI)
Priority (15min)	90387	214611	18242	2013
Priority (45min)	95309	182877	17939	1979
FIFO (15min)	89213	184623	16594	1831
FIFO (45min)	88277	151027	15944	1759

\* Risk is defined as the sum of expected consequences expressed in dollar terms.

The observation of risks in the terminal region (zone 4) is also important. Policies mostly show their immediate response to risks at the entrance but the risk behavior may change as the vessels move towards their destination terminals. Figure 4.11 to Figure 4.13, and

Table 4.6 to Table 4.8 exhibit risk behaviors of the four scenarios in Cases A through C in zone 4. As expected, all four scenarios exhibit lower risks in zone 4 when compared to zone 1.

Figure 4.11 displays the instantaneous risks in zone 4 in Case A. Similar to the observation in zone 1 of this case, there are risk spikes produced at the reopening and instantaneous risk distribution sits on a higher band for the period after reopening.

Table 4.6 shows average risks and related statistics of the four pursuit distance scenarios in zone 4. Maximum instantaneous risk is the highest in the Priority (15 min.) scenario since more tankers entering in the river accumulate in the terminal region in a shorter time compared to other scenarios. Again, the FIFO (45 min.) scenario is producing the lowest risks as expected. Nevertheless, average risks in all scenarios are similar to each other. The slightly higher average risk in the Priority (45 min.) scenario is possibly due to accumulation of more tankers in the system for a longer period, as it is also discussed for zone 1.



Figure 4.11 - Zone 4 instantaneous risks between days 300 and 320 in Case A (Full Closure)

Table 4.6 - Zone 4 average risks within the period between days 308 and 320 in Case A (Full Closure)

Scenario	Average Risk	Maximum Risk	Standard Deviation	Half Width (95% CI)
Priority (15min)	51950	96752	11387	1309
Priority (45min)	53319	88896	11099	1276
FIFO (15min)	52451	85958	11020	1267
FIFO (45min)	48201	80442	10063	1157

\* Risk is defined as the sum of expected consequences expressed in dollar terms.

The instantaneous risks in Case B are displayed in Figure 4.12 for the four scenarios. In this case, maximum instantaneous risks are lower than Case A. In Table 4.7, average risks for the post-incident period are given. In this case, all four scenarios are producing

similar risk values. The average risks are also comparable to Case A whereas maximum instantaneous risks are a bit lower than Case A.



Figure 4.12 - Zone 4 instantaneous risks between days 300 and 320 in Case B (Full Closure and Delay in Inbound)

Table 4.7 - Zone 4 average risks within the period between days 308 and 320 in Case B (Full Closure and Delay in Inbound)

Scenario	Average Risk	Maximum Risk	Standard Deviation	Half Width (95% CI)
Priority (15min)	52864	83168	11027	1268
Priority (45min)	48731	82387	9857	1133
FIFO (15min)	52174	76555	10299	1184
FIFO (45min)	50881	84172	11383	1309

\* Risk is defined as the sum of expected consequences expressed in dollar terms.

Finally, Figure 4.13 and Table 4.8 exhibit risk behavior of the four scenarios for Case C. The figure shows risk spikes similar to Case A, but the distribution of risks after the reopening is much similar to the distribution of risks prior to the incident. This can also be observed from the table since the average risks are less than other two cases.

Table 4.8 indicates, maximum instantaneous risks are lower in the 45-minute pursuit distance scenarios. However, average risks are similar to each other in all scenarios. When the average risks are compared to other cases, Case C exhibits the lowest average risks for zone 4, as it is the same for zone 1.



Figure 4.13 - Zone 4 instantaneous risks between days 300 and 320 in Case C (Partial Closure)

Scenario	Average Risk	Maximum Risk	Standard Deviation	Half Width (95% CI)
Priority (15min)	48252	94216	10221	1128
Priority (45min)	49294	84076	10295	1136
FIFO (15min)	48543	97200	9780	1079
FIFO (45min)	48150	83607	8698	960

Table 4.8 - Zone 4 average risks within the period between days 307 and 320 in Case C (Partial Closure)

\* Risk is defined as the sum of expected consequences expressed in dollar terms.

# 4.8. Conclusion for Vessel Prioritization

In this chapter, the issue of vessel prioritization is studied through an incident similar to the case of Athos I, which happened in Paulsboro in November of 2004. The simulation based risk model is employed for estimating the performance and risk measures. Three cases are considered, two with a major oil spill and cleanup effort (Cases A and B) and the other with medium level environmental consequence (Case C). The duration of the closure is assumed to be 3 days for Cases A and B as in the case of Athos I, and 2 days for Case C.

Throughout the reopening process after disruption, extensive numerical experimentation is carried out focusing on prioritizing tankers and refrigerated vessels in entrance queues (referred to as closure queues) and on vessel pursuit distances, which is the time interval between consecutive vessels entering the system. For each case considered, scenarios are developed to examine effects of prioritization and pursuit distance on the port performance as well as on the risk performance. Several measures are defined to examine the impact of closure cases and scenarios on the port performance. Clearance time of the closure queue and total time to normal are important measures to observe the impact of different closure cases and the pursuit distance employed. Total number of vessels in queue is an essential measure providing the information of accumulation at the entrance for the authorities to be prepared for a waiting area for the vessels. Cumulative waiting time of vessels helps to understand total time cost of closure to trade operations. At last, waiting time for each vessel type assists evaluating the effect of prioritization.

Since the concentration is on several days after reopening, instantaneous risks are in focus to observe risk impact of reopening policies. Therefore, scenarios are evaluated through their maximum instantaneous risk impact as well as the average risk observed within the period after reopening till the system returns to normal operation.

Closure policy (i.e. complete or partial closure) has the critical impact on the total number of vessels kept waiting in the queue. In the complete closure with delaying inbound vessels case (Case B) employing a conservative pursuit distance policy may cause more than 60 vessels in total to wait in the queues. However, this observation does not take into account possible communication and coordination to slow down vessels before they arrive into port. Among all cases, partial closure (Case C) is the most desirable due to the lowest waiting times, queue clearance times as well as times to normal. In any policy, the results point out the importance of planning, communication, and imposing regulations for the waiting area.

Pursuit distance policy has the major influence on queue clearance times. Increasing pursuit distance from 15 minutes to 45 minutes brings about almost four times increase in closure queue clearance time. Therefore, an extremely cautious policy while reopening and permitting vessels in the river may cause excessive amount of queue clearance time.

For each pursuit distance scenario, prioritizing vessels do not change port performance measures in general compared to first-come-first-served basis, and result in targeted shorter waiting times for priority vessels.

Risk estimations and discussions guide us to conclude that placing tankers into closure queue with higher priorities eventually moves them into the channel within close proximity of each other, and thereby increases the instantaneous risks at the Breakwater entrance and the lightering area (zone 1), and slightly impacts the risks at the terminals region (zone 4) in the same direction.

Closure policy has the most important impact in managing risks. When all cases are compared, partial closure policy (Case C) is producing the lowest average as well as the lowest maximum risks. In this policy, the average risks are almost at the same level as the current average risks at the entrance region (zone 1) whereas they are about 30% to 40% higher in the other policy cases (Cases A and B).

Pursuit distance and the service discipline (i.e. Priority or FIFO) have similar risk influence on maximum instantaneous risks. Larger pursuit distances and FIFO service discipline reduces maximum risks in general. However, their effect on the average risks is more complicated due to interaction with other system components. For instance, larger pursuit distances (e.g., 45 minutes) in the Priority scenarios tend to increase average risks and reduce maximum risks in full closure (Case A) and in partial closure cases (Case C). Nevertheless, larger pursuit distances may still be preferable due to lower maximums which are disaster indicators. Full closure with delay in inbound case (Case B) is special in the sense that it empties the system out until some number of vessels remains, and then opens the queue. A larger pursuit distance scenario may be preferred in this case not only due to a smaller maximum but also a smaller average risk.

While recovering from a river closure, prioritizing vessels is unavoidable due to several factors such as security reasons, efficiency purposes and especially commodity needs. Thus, in addition to closure policies decisions regarding priorities as well as vessel pursuit distances need to be made for a safe and rapid resumption of trade. Closure policies may be dependent on the incident responsible for closure but a policy closer to the normal operation, such as partial closure (Case C) produces best performance in terms of efficiency and risks. In order to mitigate maximum risks, a policy that lets the system empty itself out before permitting vessels in (such as in Case B) demonstrated its effectiveness. Prioritization helps reducing the waiting time of targeted vessels but as in the instance of tankers it may increase risks slightly depending on the case. On the other hand, pursuit distances may be based on other factors such as pilot availability, yet larger intervals reduce port performance and in return helps to mitigate risks. Thus, one may

in effective resumption of trade resulting in better performance for critical cargo vessels (e.g., tankers) in the sense of port performance and manageable risks.

As Modares (2008) points out, the primary objective of a risk assessment study is not necessarily the estimation of actual risk values but it may be the identification of system components contributing to the risks, and evaluation of effectiveness of possible policies to mitigate risks. As it is critically mentioned in SAFE Port Act of 2006 Section 202, this chapter aims to provide insight for development of tactical plans, to support risk management strategies since it deals with balancing the conflicts in policies, and to demonstrate need to deploy analytical methodologies to investigate trade-offs during preparing port recovery plans.
## 5. MODELING VESSEL ARRIVALS

Arrival processes are one of the most critical components of modeling ports and waterways. In most studies, input processes are represented by independent and identically distributed (i.i.d.) random variables even though data suggest correlation structures. This is mainly because of complexity of generating correlated processes. On the other hand, arrival processes play an important role on the overall system performance as well as on the risk assessments.

Vessel arrivals at ports and waterways are typically scheduled by terminal operators in a way to maintain base stock levels and to achieve a planned throughput for a given time period. Therefore it is not surprising that arrival stream to a terminal shows time dependency and correlation structures. In this regard, modeling of vessel arrivals in port simulation studies requires special attention in order to develop valid models.

In the simulation model developed for Delaware River and Bay, correlations on vessel arrivals are found not significant for most of the vessel types, and in few cases due to rare visits into the port correlations are neglected. However, for other similar studies modeling of input processes may require correlations to be taken into account for developing valid models. In order to demonstrate such a case, vessel arrivals to a bauxite terminal at Port Trombetas<sup>6</sup> in Brazil are considered. Through a test case, the impact of modeling vessel arrivals on port performance is illustrated. Thus, this may also indicate the importance of input modeling on simulation based risk assessment studies.

<sup>&</sup>lt;sup>6</sup> ATZ, Capacity expansion study for Mineracao Rio do Norte S.A., Brazil, Technical Report, New York (1996)

In literature, vessel arrival processes at terminals are studied with reference to the real life practice at ports and waterways. These processes are characterized with one-dimensional point processes by Lewis (1961) and Govier and Lewis (1960, 1963) and their second order and correlation properties are investigated by Cox and Lewis (1966) and Nelsen and Williams (1970). Recently, Jagerman and Altiok (2003) used these processes in the queuing analysis of ports handling bulk materials.

In this chapter, our focus is modeling vessel arrivals with specific negative correlation properties for use in simulation studies based on available data (or statistics) on mean interarrival time, variance and correlations.

## 5.1. Impact of Modeling Vessel Arrivals on Queuing Performance

Input analysis plays a vital role in the validity of models to study a real life situation. To illustrate the impact of different arrival processes on system performance a test case is considered with a simple queueing problem using the vessel arrival data at Port Trombetas in Brazil. From the actual observations of 364 vessels for a year the characteristics of the interarrival times (*X*) data are given in Table 5.1. The data suggests a mean interarrival time of 1 day with squared coefficient of variation ( $Cv^2$ ) of 0.5143 (as a measure of dispersion) and a negative correlation of 0.164 at lag 1.

Table 5.1 - Port	Trombetas vesse	el interarrival tim	nes data statistics
	E[X]	24 hours	

 E[X]
 24 hours

  $Cv_X^2 = \frac{\sigma_x^2}{\mu_X^2}$  0.5143

  $\rho_X(1)$  -0.164

Three different cases are considered to model this arrival process. In the first case, the actual observations are used to generate the arrival stream. In the second case, the interarrival data is assumed independent and the Weibull distribution is fit to the original data with the scale parameter  $\beta = 26.4$  and the shape parameter  $\alpha = 1.41$  resulting in the  $Cv^2$  at 0.515. This case is assuming no correlation between arrivals but matching the original  $Cv^2$  which represents the most common approach in input data modeling through assuming independent arrivals and fitting a probabilistic distribution to the data on hand. The third case considers the unrefined approach assuming Poisson arrivals, mostly applied when no data is available. In this case, interarrival times are exponentially distributed matching the mean interarrival time of 24 hours and a  $Cv^2$  of 1. In order to achieve a 0.75 utilization service time (loading / unloading time) distribution is assumed to be the Erlang distribution with shape parameter k = 4 and scale parameter  $1/\lambda = 18$  hours. This simple queuing problem is modeled using Arena simulation tool and results are collected through 1 year runs with 100 replications.

The results on queuing performance of these three cases are given in Table 5.2. Average queue waiting times ( $\overline{W}$ ) and maximum waiting times indicate that there is a significant

difference among these cases in terms of queuing performance. Thus, this test case demonstrates the impacts of modeling an arrival process, even in a simple queuing problem, and raises the question how can this type of a process be modeled to approximate realistic performance results?

Vessel Arrival Model	Average Waiting Time $(\overline{W})$ (hours)	Maximum Waiting Time (hours)	
Actual Data ( $CV_x^2 = 0.514, \ \rho_x(1) = -0.164$ )	$12.475 \pm 0.417$	126.35	
Weibull ( $\beta = 26.4, \alpha = 1.41$ ) ( $CV_x^2 = 0.515, \rho_x(1) = 0$ )	18.444 ± 1.169	241.00	
Exponential ( $\lambda = 1/24$ ) ( $CV_x^2 = 1, \ \rho_x(1) = 0$ )	31.325 ±169	336.58	

Table 5.2 - Results of simulation runs of test cases

## **5.2.** Vessel Arrivals at Ports and Waterways

Vessel arrival patterns are one of the most important factors affecting port performance at terminals. In practice, vessels arrivals are planned at terminals to handle specified amount of cargo in a particular time frame to achieve expected throughput. That is, a limited number of vessels are scheduled in a fixed period of time (e.g., 30 vessels per month) considering uncertain times of berth operations since idling a vessel at anchorage is a major cost element. On the other hand, timeliness of vessel arrivals is also affected by many factors such as trade routes, weather conditions, tidal activity, unexpected failures

and others resulting mismatch in scheduled times of vessels. In this regard, vessel arrivals at terminals are handled by assigning a window of arrival, *lay period*  $\omega$ , for each vessel with respect to a fixed scheduled time and vessels may arrive at any time within that window.

The process is illustrated in Figure 5.1 and can be formally expressed as follows as it is described in Jagerman and Altiok (2003). Let the scheduled interarrival time between the vessels is expressed as *a*, then  $\varepsilon_i = ia$  defines the scheduled arrival time of the *i*<sup>th</sup> vessel. That is, arrivals are scheduled *a* time units apart from each other. Let  $Y_i$  be the elapsed time and its cumulative distribution function is  $F_Y$ . Then for the moment let us assume  $Y_i$  is uniformly distributed in (0,  $\omega$ ) within its window of arrival  $\omega$ . Then  $A_i$  denotes the actual arrival time of the *i*<sup>th</sup> scheduled vessel and can be expressed as follow:

$$A_i = -b_0 + i \cdot a + Y_i, \quad i = ..., -2, -1, 0, 1, 2, ...$$
 (5.1)

where  $b_0$  is a constant equal to the realization of the random variable  $Y_0$  in order to fix the origin at t = 0. Then  $A_0 = 0$  is the initial arrival event at t = 0 which is scheduled to arrive at  $-y_0$ .



Figure 5.1 - Arrival time of the  $i^{th}$  vessel

Notice that, the order of actual arrivals can be different from the scheduled order. This is due to overlapping lay periods of different vessels as can be seen in Figure 5.2. This occurs depending on the form of the  $Y_i$  distribution and its variance  $\sigma_{Y_i}$ . The swapping of arrivals can be observed more often when  $\sigma_{Y_i}/a$  ratio increases.



Figure 5.2 - Vessel arrival process at ports and waterways

The swapping phenomenon completely changes the characteristics of the process as it is demonstrated with an example in Figure 5.3. When intervals between the arrival time of  $i^{th}$  and  $(i-1)^{st}$  scheduled vessels are considered, the sequence constitutes a simple movingaverage where  $X_i = a + Y_i - Y_{i-1}$ . This might be referred to as the theoretical process. On the other hand, the observed process becomes quite complicated when  $X_j$  is defined as the interarrival time between the  $j^{th}$  and  $(j-1)^{st}$  vessel arrivals, where j represents the order of arrivals as we observe them. Clearly, the observed process is the same as theoretical process when lay period is less than the scheduled interarrival time or  $\sigma_Y \ll a$ , that is when there is no swapping. In this chapter our interest is in the observed process where the variance and correlation properties cannot be calculated analytically except for special cases. That is, the relevant probabilistic properties of the process can be derived, but to get practically useful results approximations have to be made.



Figure 5.3 - An example comparing theoretical and observed processes

Properties of this (observed) process have been developed by Lewis (1961) and Govier and Lewis (1960, 1963) where the events they were concerned are the arrival of oil tankers at an oil terminal. Cox and Lewis (1966) shows that  $\{X_j\}$  is a stationary sequence of identical random variables and the counting process N(t), being conditioned on  $b_0$ , is non-stationary in continuous time. On the other hand, when time zero is an arbitrary chosen point the number of arrivals in a period of length t,  $N_e(t)$ , is a stationary counting process.

When p(k, t) is defined as the probability distribution of  $N_e(t)$ , that is *k* arrivals in a period of length *t*, the variance and the autocorrelation coefficients  $\rho_i$  of the interarrival times  $X_j$  are given based on p(k, t) as follows:

$$E[X] = a, \qquad Var[X] = \int_0^\infty p(0,t)dt - a^2$$
(5.2)

and

$$\rho_{i} = a \frac{\int_{0}^{\infty} p(i,t)dt - a}{Var[x]}, \qquad i = 1, 2, ..$$
(5.3)

In the observed process, it was shown that  $\rho_i < 0$ , for all *i* and  $\sum_{i=1}^{\infty} \rho_i = -0.5$  whereas  $\rho_i = -0.5$  and  $\rho_i = 0$  for i > 1 in the theoretical process (or when  $\sigma_Y << a$ ) as it is shown in the example in Figure 5.3. The limiting form is indicated in Lewis (1961) for given *a* that as  $\sigma_Y \rightarrow \infty$  the process is Poisson with mean interval *a*.

Jagerman and Altiok (2003) used the squared coefficient of variation,  $Cv_x^2 = Var[X]/a^2$ , as a key measure of dispersion for interarrival times in modeling of vessel arrivals. They have tried to match  $Cv_x^2$  and lag 1 correlation,  $\rho_X(1)$ , properties of actual data using the scheduled arrivals with lay period model. Assuming elapsed time  $Y_i$  is uniformly distributed in  $(0, \omega)$ , the behavior of  $Cv_x^2$  and  $\rho_X(1)$  are investigated using simulation. That is, the underlying arrival process is modeled using simulation, and variance and correlation properties are observed for various levels of lay period  $\omega$ . This approach is employed in order to fit the characteristics of the actual interarrival time data used in the test case of Section 5.1. When a = 1 day, different values of  $\omega$  are tested as given in Table 5.3.

ω	2	3	4	7	10	12	15
$Cv_X^2$	0.42	0.56	0.64	0.77	0.83	0.86	0.88
$\rho_X(1)$	-0.42	-0.3	-0.23	-0.13	-0.1	-0.08	-0.07

Table 5.3 -  $Cv_X^2$  and  $\rho_X(1)$  values for different values of  $\omega$  when a = 1 day

As seen from the table, as  $\omega$  increases,  $Cv_X^2$  increases and lag 1 correlation approaches 0. When matching the  $Cv_X^2$  of the actual data is more important, the best fit could be achieved at  $\omega = 2.65$  where  $Cv_X^2 = 0.52$  and  $\rho_X(1) = -0.34$ . That is, modeling the actual vessel arrival stream with the underlying process can produce arrivals with a matching variation but lag 1 correlation is doubled compared to actual value  $\rho_X(1) = -0.164$ . When Table 5.3 compared to actual data statistics given in Table 5.1, it seems that it is not possible to fit both  $Cv_X^2$  and  $\rho_X(1)$ . This shows, using single parameter  $\omega$  is not enough to match both  $Cv^2$  and  $\rho_I$  of the data. In this chapter, this process is investigated and improved relying on all the assumptions and characteristics mentioned above. Independent elapsed time distribution of vessels is relaxed and a time series characteristic is implemented to the elapsed time distribution. This way, the performance of the model to represent variation and correlation properties of the actual data will be improved.

### 5.3. A Modified Process of Scheduled Arrivals with Lay Period

Scheduled arrivals with lay period process described in Equation 5.1 is modified by introducing a  $\theta$  parameter making the elapsed time component similar to a moving average model. The modified process where  $A_i$  denotes the actual arrival time of the  $i^{\text{th}}$  scheduled vessel is expressed as follows.

$$A_{i} = -b_{0} + i \cdot a + Y_{i} + \theta \cdot Y_{i-1}, \qquad i = \dots, -2, -1, 0, 1, 2, \dots$$
(5.4)

In the original model, the elapsed times in lay periods of different vessels are independent and identically distributed. Through addition of parameter  $\theta$ , elapsed times of different vessels are now dependent to each other. This, in turn helps to control the correlation structure of the resulting observed process. In the modified process, the elapsed time within its window of arrival is defined as  $Y_i + \theta Y_{i-1}$  where  $Y_i$  is again assumed uniformly distributed in  $(0, \omega)$ . Note that  $\varepsilon_i = ia$  still continues to define the scheduled arrival time of the *i*<sup>th</sup> vessel. Although there is no theoretical evidence  $N_e(t)$ , the number of arrivals in a period of length *t*, still seems to be a stationary counting process when time zero is an arbitrarily chosen point based on simulation test results. The process is illustrated in Figure 5.4.



Figure 5.4 - Arrival time of the  $i^{th}$  vessel with the modified process

Deploying the modified process and testing using simulation to fit the characteristics of the actual interarrival time data used in the Port Trombetas test case in Section 5.1, best fit is achieved at  $\omega = 2.5$  and  $\theta = 0.44$  where  $Cv_X^2 = 0.515$  and  $\rho_X(1) = -0.164$ . This shows, using the parameter  $\theta$  helps to better match  $Cv^2$  and  $\rho_I$  of the actual data.

## **5.3.1.** Impact of $\omega$ and $\theta$ on $Cv^2$ and $\rho(1)$

In the modified scheduled arrivals with lay period model, once the scheduled interarrival time between the vessels is set as *a*, there are two parameters  $\theta$  and  $\omega$ , to control the properties of the process. That is, in the resulting process, the observed vessel arrivals have mean interarrival time *a*, and variation and correlation properties are determined by the two parameters  $\theta$  and  $\omega$ . As it was used by Jagerman and Altiok (2003) the dispersion of interarrival times can be measured using  $Cv^2$  and correlation properties are observed only at lag 1 at this level.

The behavior of  $Cv_X^2$  is depicted in Figure 5.5 when a = 1 day for varying levels of  $\omega$  and  $\theta$ . As  $\omega$  and  $\theta$  increases,  $Cv_X^2$  gets bigger since both parameters increase the variance in the process.



Figure 5.5 -  $Cv_X^2$  values of the observed process when a = 1 for levels of  $\omega$  and  $\theta$ 

The change of  $\rho_X(1)$  is shown in Figure 5.6 when a = 1 day for different levels of  $\omega$  and  $\theta$ . As  $\omega$  and  $\theta$  increases lag 1 correlation approaches 0.



Figure 5.6 -  $\rho_X(1)$  values of the observed process when a = 1 for levels of  $\omega$  and  $\theta$ 

Note that when  $\theta = 0$ , the modified process is the same as the original scheduled arrivals with lay period process. Figure 5.7 represents  $Cv_X^2$  and  $\rho_X(1)$  values in one graph for varying levels of  $\omega$  for the case of a = 1 and  $\theta = 0$ . This graph is helpful to show the range of  $Cv_X^2$  and  $\rho_X(1)$  values that can be modeled using the original scheduled arrivals with lay period process.



Figure 5.7 -  $Cv_X^2$  and  $\rho_X(1)$  values for levels of  $\omega$  when  $\theta = 0$ 

Figure 5.8 represents  $Cv_X^2$  and  $\rho_X(1)$  values in one graph for varying levels of  $\omega$  and  $\theta$  for the case of a = 1 and  $0 \le \theta \le 1$ . This figure shows the feasible region of  $Cv_X^2$  and  $\rho_X(1)$ values that can be modeled using the modified scheduled arrivals with lay period process. That is, if  $Cv_X^2$  and  $\rho_X(1)$  values of arrival data fall into this region, it is possible to find corresponding  $\omega$  and  $\theta$  parameters to express the arrival stream using the modified process.



Figure 5.8 -  $Cv_X^2$  and  $\rho_X(1)$  values for selected levels of  $\omega$  when  $0 \le \theta \le 1$ 

# **5.3.2.** Matching $Cv^2$ and $\rho(1)$ using $\omega$ and $\theta$

The analysis up to this point shows that the modified process of scheduled arrivals with lay period can be used to model vessel arrivals in port simulation studies. The benefit of using the modified process is due to its ability to better match variation and correlation properties of the actual arrival data. However, recall that the second order properties of this process such as variation and correlation properties cannot be calculated except for special cases. In this regard, once the statistics on actual data are obtained, modeling of vessel arrivals using the scheduled arrivals with lay period has to be done based on empirical analysis. That is,  $\omega$  and  $\theta$  parameters defining the underlying model have to be

approximated using experiments while the scheduled interarrival time, *a*, remains simply as the mean interarrival time of the actual data.

In this chapter, simulation models are built to represent the modified process of scheduled arrivals with lay period using the Arena simulation tool. That is, based on Equation 5.4 once the scheduled interarrival time is set as *a*, and given the  $\omega$  and  $\theta$  parameters of the underlying model, the simulation model generates arrival data points. Then, based on the observed orders interarrival times ( $X_j$ ) are recorded, and  $Cv_X^2$  and  $\rho_X(1)$  are calculated in the model. Table 5.4 provides a sample data set for the simulation process. A sample size of 50,000 is used in the simulation experiments.

Scheduled Order (i)	(Y <sub>i</sub> ) ~ UNIF(θ,ω)	Arrival Time (A <sub>i</sub> )	Observed Order (j)	Arrival Time (A <sub>j</sub> )	Observed Interarrival Time (X <sub>j</sub> )
1	0.414	1.414	1	1.414	
2	1.669	3.851	2	3.851	2.438
3	2.420	6.154	3	5.468	1.617
4	0.403	5.468	4	5.954	0.486
5	0.776	5.954	5	6.154	0.201
6	1.003	7.344	6	7.344	1.190
7	1.522	8.963	7	8.963	1.619
8	0.923	9.593	8	9.593	0.630
<i>a</i> = 1	$\omega = 2.5$	$\theta = 0.44$	E[X] = 1	$Cv_X^2 = 0.515$	$\rho_X(1) = -0.164$

Table 5.4 - A sample data set for the modified process of scheduled arrivals with lay period

Simulation model provides  $Cv_x^2$  and  $\rho_x(1)$  results for a given process with parameter set  $(a, \omega, \theta)$ . However, matching  $Cv^2$  and  $\rho(1)$  statistics of the actual data and finding the  $\omega$  and  $\theta$  parameters (since *a* is already known) of the underlying process requires a structured multidimensional search algorithm. That is, each parameter set  $(a, \omega, \theta)$  maps a  $Cv_x^2$  and a  $\rho_x(1)$  that requires searching for the  $\omega$  and  $\theta$  parameters matching  $Cv^2$  and  $\rho(1)$  statistics of the actual data. This also involves running the simulation model each time a parameter set needs to be tested since there is no analytical representation for this process. Hooke and Jeeves (1961) algorithm is implemented for this purpose as a direct-search method which uses only function values. Thus, each time a parameter set is tested, a simulation run is performed and the results are passed to the search algorithm. Hooke and Jeeves algorithm is developed using Visual Basic for Applications (VBA) and integrated with the simulation.

The method of Hooke and Jeeves adopts a simple scheme involving functional evaluations. A summary of the algorithm is given below according to Bazaara et al. (2006).

## **Initialization Step**

Let  $d_i = d_1, \dots, d_n$  be the coordinate directions.

A scalar  $\varepsilon > 0$  is to be used for terminating the algorithm.

Initial step size  $\Delta \ge \varepsilon$  and an acceleration factor  $\alpha > 0$  are chosen.

While  $\mathbf{x}_1$  is the starting point, let  $\mathbf{y}_1 = \mathbf{x}_1$ ,

Let iteration k = 1 and start with direction j = 1.

Go to the Main Step.

#### Main Step

1. If  $f(\mathbf{y}_j + \Delta \mathbf{d}_j) < f(\mathbf{y}_j)$ , the trial is a success,

then let  $\mathbf{y}_{j+1} = \mathbf{y}_j + \Delta \mathbf{d}_j$  then go to Step 2.

If  $f(\mathbf{y}_j + \Delta \mathbf{d}_j) \ge f(\mathbf{y}_j)$ , the trial is a failure

If  $f(\mathbf{y}_j - \Delta \mathbf{d}_j) < f(\mathbf{y}_j)$ , then let  $\mathbf{y}_{j+1} = \mathbf{y}_j - \Delta \mathbf{d}_j$ , and go to Step 2.

If  $f(\mathbf{y}_j - \Delta \mathbf{d}_j) \ge f(\mathbf{y}_j)$ , then let  $\mathbf{y}_{j+1} = \mathbf{y}_j$ , and go to Step 2.

2. If j < n, then let j = j + 1, and repeat Step 1.

Otherwise,

If  $f(\mathbf{y}_{n+1}) < f(\mathbf{x}_k)$ , then go to Step 3

If  $f(\mathbf{y}_{n+1}) \ge f(\mathbf{x}_k)$ , then go to Step 4

3. Let  $\mathbf{x}_{k+1} = \mathbf{y}_{n+1}$ , and let  $\mathbf{y}_1 = \mathbf{x}_{k+1} + \alpha (\mathbf{x}_{k+1} - \mathbf{x}_k)$ .

Let iteration k = k + 1 and start with direction j = 1.

Go to Step 1.

4. If  $\Delta \leq \varepsilon$ , STOP.  $\mathbf{x}_k$  is the solution.

Otherwise, let  $\Delta = \Delta / 2$ .

Let  $\mathbf{y}_1 = \mathbf{x}_k$  and  $\mathbf{x}_{k+1} = \mathbf{x}_k$ .

Let iteration k = k + 1 and start with direction j = 1, and repeat Step1.

In this algorithm steps 1 and 2 are described as explanatory search while step 3 is an acceleration step through the direction  $\mathbf{x}_{k+1}$  -  $\mathbf{x}_k$ .

Hooke and Jeeves algorithm is initiated with a starting point, target values (associated with an objective function) and search parameters such as termination criteria, initial step size and acceleration factor which might also be changed by the user. Through several iterations algorithm converges to an optimal point which gives user  $\omega$  and  $\theta$  parameters to match the targeted  $Cv^2$  and  $\rho(1)$  statistics of the actual data. A three-dimensional sample search surface (response surface) for the Port Trombetas test case is illustrated in Figure 5.9. The optimal point (depicted with a star in the figure) forms at  $\omega = 2.5$  and  $\theta = 0.44$  and results in  $Cv_X^2 = 0.515$  and  $\rho_X(1) = -0.164$  which gives the best fit using the modified process. Recall that the Port Trombetas actual data have  $Cv_X^2 = 0.5143$  and  $\rho_X(1) = -0.164$ .



Figure 5.9 - The search surface for the Port Trombetas test case

## **5.3.3.** Impact of $\omega$ and $\theta$ on Correlations at Other Lags

So far only lag 1 correlation is considered in the analysis due to its use in literature and its impact on the queueing performance. It is already observed that lag 1 correlation approaches to 0 as  $\omega$  and  $\theta$  increases. In this section the behavior of correlations at other lags ( $\rho_X(i)$  values when i > 1) are investigated based on varying values of parameters  $\omega$  and  $\theta$ .

In Figure 5.10 the impact of parameter  $\omega$  on correlations at other lags is depicted when a = 1 and  $\theta = 0$ . The figure shows as  $\omega$  increases correlation at lag 1 moves to other lags. Also, as  $\omega$  keeps increasing correlations at other lags decrease which in turn enhance higher order correlations. However, sum of correlations remains around -0.5 at all cases. Note that, for higher values of  $\omega$  (such as 16 or 100) higher level correlations are not depicted in the figure.



Figure 5.10 - Impact of  $\omega$  on correlations when a = 1 and  $\theta = 0$ 

In Figure 5.11, the impact of  $\theta$  on correlations at other lags is shown when a = 1 and  $\omega = 4$ . It can be seen that as  $\theta$  increases correlation at lag 1 slightly moves to other lags and generates higher level correlations. However, notice that  $\theta$  mostly modifies lag 1 correlation and again the sum of all correlations remains around -0.5 at all cases.



Figure 5.11 - Impact of  $\theta$  on correlations when a = 1 and  $\omega = 4$ 

# **5.3.4.** Matching $Cv^2$ , $\rho(1)$ and $\rho(2)$

In the view of the observations on impact of  $\omega$  and  $\theta$  on correlations, one may conclude that if higher order correlations are of interest, the modified process can be extended introducing new parameters. In case correlation at lag 2 is concerned, this might be achieved through introducing a  $\theta_2$  parameter and defining a new window of arrival for a vessel as  $Y_i + \theta_1 Y_{i-1} + \theta_2 Y_{i-2}$  where  $Y_i$  is again assumed uniformly distributed in  $(0, \omega)$ . Then the new extended process can be defined as follow:

$$A_{i} = -b_{0} + i \cdot a + Y_{i} + \theta_{1} \cdot Y_{i-1} + \theta_{2} \cdot Y_{i-2}, \quad i = \dots, -2, -1, 0, 1, 2, \dots$$
(5.5)

Using Equation 5.5, it is expected to match higher order correlations and this is tested by fitting the model for the Port Trombetas data. The actual data suggests that  $\rho_X(2)$ , the correlation at lag 2, is -0.075. Through empirical testing with the extended model a parameter set (a = 1,  $\omega = 2.65$ ,  $\theta_1 = 0.453$ ,  $\theta_2 = 0.32$ ) is obtained to produce  $Cv_X^2 = 0.52$ ,  $\rho_X(1) = -0.165$  and  $\rho_X(2) = -0.07$ . This shows that if the characteristics of the data on hand conform with the characteristics of the scheduled arrivals with lay period process, it is possible to achieve a fairly accurate modeling of the arrival stream.

Finally, queuing implications of different approaches in modeling arrival data are compared based on the Port Trombetas data. Queueing analysis is performed as it is explained in Section 5.1 and the results are summarized in Table 5.5. In the first case the original data is directly used for the arrival stream. The Weibull case assumes independent arrivals while it matches the  $Cv_X^2$  of the original data. The other cases use the scheduled arrivals with lay period process and matches  $Cv_X^2$ ,  $\rho_X(1)$  and  $\rho_X(2)$  step by step. As can be seen from the table, the closest performance to actual data results is achieved through matching all  $Cv_X^2$ ,  $\rho_X(1)$  and  $\rho_X(2)$ .

	Average	Maximum	
Vessel Arrival Model	Waiting Time	Waiting Time	
	$(\overline{W})$ (hours)	(hours)	
Actual Data	12 475 + 0 417	106.25	
$(CV_x^2 = 0.514, \rho_x(1) = -0.164, \rho_x(2) = -0.075)$	$12.475 \pm 0.417$	126.35	
Weibull ( $\beta = 26.4, \alpha = 1.41$ )	19 444 + 1 160	241.00	
$(CV_x^2 = 0.515, \rho_x(1) = 0)$	$16.444 \pm 1.109$		
Matching $Cv_X^2$			
$(\omega = 2.65)$	$10.821 \pm 0.368$	140.97	
$(CV_x^2 = 0.52, \rho_x(1) = -0.34, \rho_x(2) = -0.14)$			
Matching $C v_X^2$ and $\rho_X(1)$		137.88	
$(\omega = 2.5, \theta = 0.44)$	$11.668 \pm 0.283$		
$(CV_x^2 = 0.515, \rho_x(1) = -0.164, \rho_x(2) = -0.24)$			
Matching $Cv_X^2$ , $\rho_X(1)$ and $\rho_X(2)$			
$(\omega = 2.65, \theta_1 = 0.453, \theta_2 = 0.32)$	$12.381\pm0.382$	122.86	
$(CV_x^2 = 0.52, \ \rho_x(1) = -0.165, \ \rho_x(2) = -0.07)$			

Table 5.5 - Results of simulation runs of test cases with modified process

## 5.4. Conclusion on Modeling Vessel Arrivals

The final analysis on queueing performance of vessel arrival models indicates the importance of variation and correlation characteristics of the arrival stream on the system performance. This also suggests arrival processes can be critical in risk assessments since port performance is closely related to the risk estimations. In the absence of general purpose methods for representing and generating dependent arrival processes, the study

presented in this chapter aimed to provide a practical approach to model arrival processes showing special negative correlation characteristics.

The scheduled arrivals with lay period process, introduced earlier in literature with reference to real life practice of vessel arrivals to ports, is a practical approach to use in simulation studies especially due to their ability to represent negative correlation structures. However, it is shown that this original process is inadequate to fit both variation and correlation properties of the actual data at the same time. In this regard, the original process is modified introducing new parameters. The properties of this modified process are investigated and it is shown that it has a better feasible region to capture both variation and correlation properties. A computer program is developed using VBA to estimate all the parameters for the modified model having targeted variation and lag 1 correlation properties. It is also presented that the modified process could be extended to fit higher correlation properties through introducing new parameters.

A potential future work on this topic might be investigation of further characteristics of the modified process to improve the feasible region to map combinations of variation and correlation properties. Another direction to study is to improve the methodology to fit higher order correlations.

## 6. CONCLUSION AND FUTURE RESEARCH

In this dissertation, quantitative analyses on performance and safety risk issues of the vessel traffic on ports and waterways are performed through the case of Delaware River and Bay.

Delaware River has a major port system in the East Coast of the U.S. with more than 40 port facilities and receiving around 3,000 vessels every year. Sixty-five percent of the region's cargo tonnage is petroleum, and the incoming traffic brings around 12% of the nation's crude imports, making the port one of the most critical petroleum infrastructures in the U.S. Together with the other container and bulk cargo facilities, it is one of the largest general cargo port complexes in the nation.

To begin, the vessel traffic system was analyzed and a simulation model was developed to constitute an accurate platform mimicking the overall system in order to perform scenario and policy analysis to study the key issues regarding the port's operation. Emphasis is given to adaptive and parametric modeling of the major components. The simulation modeling chapter elaborates on realistic representation of all these components, which are mostly common to other ports and waterways, such as vessel arrivals, characterization of various types of vessels, itinerary generation and terminal reservations, modeling of lightering and barge operations, as well as tidal and navigational rules. Therefore, the model building phase provides a detailed road map to development of such models for other similar systems. The planned deepening in the main channel of Delaware River is considered and intertwined with possible increase in vessel arrivals due to trade growth to analyze the impacts on port performance of vessels. The results show that mainly containerships benefit from deepening and from future projections of bringing larger vessels to the system due to ample capacity in container terminals. Remarkably, tankers benefit the most from deepening and even more in the case of increased oil trade, but bringing larger tankers to the system requires substantial capacity planning, otherwise the gains may disappear. Increase in vessel arrivals brings about the usage of major anchorages almost double in the long run, if the total capacity in the port is kept the same. Deepening and shifting to a fleet of larger vessels can help to reduce anchorage calls. Yet, the temporal activity underlines the need for planning of port expansion for the long-term outlook. These results present several prospects on navigational issues that impact transportation costs based on vessel and operational efficiencies but do not go into the detail of economic impacts.

A second step is building a mathematical risk model based on probabilistic arguments with its parameters obtained using historical accident data and expert opinion elicitation. The formulation comprises the causal chain of events with all possible instigators, accidents and consequences identified from historical data. The risk model is integrated into the simulation model built to be able to evaluate risks for all possible situations generated in the simulation and to perform underlying mathematical calculations. The river is divided into six zones based on geography, infrastructure and operational activity. The simulation model is configured in such a way that in every small time interval, an observer takes a snapshot of the entire system with all the vessel activity and situational attributes. The levels of all situational attributes are continuously tracked by the simulation, thus the mathematical risk model is evaluated at that instant over each and every vessel in the system. This process is repeated long enough in simulation runs to generate a risk profile of the entire river.

The risk profile of the Delaware River on its current state is established through simulation runs. The results indicate the risks at the Breakwater entrance and the lightering area are the highest followed by the terminals region between Wilmington (DE) to Eagle Point (NJ), exhibiting about half of the risks at the entrance. The analysis shows tankers and crude handling operations are generating the major portion of the risks. Accordingly, oils spills and grounding accidents are causing the most serious consequences; environmental damage is the most hazardous outcome. In addition, for navigating vessels, the Chesapeake and Delaware Canal entrance is identified as a dangerous intersection due to high underway vessel density. These results emphasize the importance of risk-informed rather than risk-based decision making as also indicated by Apostolakis (2004).

Traffic patterns and system components change over time, however simulation models assist to interpret these complexities and dynamic interactions via controlling system parameters, employing new elements, trying scenarios and new policies. Thus, sensitivity and reaction of risk behavior are also studied through scenarios.

Based on the scenarios investigated for deepening, risk profiles for potential future projections for Delaware River are considered. The trade growth potential at the Delaware River ports indicates a 22% increase on average risks for the entire river within 30 years due to increased vessel arrivals. As expected, the river entrance and the lightering area are affected the most with 32% increase in average risks. Another potential future projection, deepening and its inherent effect of utilizing larger vessels in the main channel causes a risk profile shift within the river. The model suggests that the risks at the main entrance of the river are moving to terminals, especially to the zone between Wilmington (DE) and Eagle Point (NJ) where the most of the oil refineries are located. This interesting observation is attributed to change in the activities of larger tankers in a deeper river especially due to less lightering and increased cargo operations. When this effect is superposed with the assumed trade growth, the risk increase in this region reaches about 45% within 30 years. This change in the risk behavior stresses the subtle impacts of future projections and may raise concerns since the upstream Delaware River shores have denser population, thus it points out the need for planning on risk implications of deepening in the river.

Assessment of the effectiveness of various risk mitigation strategies is one of the main objectives of risk analysis studies. A non-traditional approach is considered for this purpose in this study. Improving operational efficiencies at the terminals resulting in shorter port times and lesser vessel density at the port is shown to reduce risks in the river. The scenario analysis indicates a 15% increase in efficiency only for tanker operations can lead to 12% average risk reduction for the entire river. This reduction may reach up 22% at the entrance zone and 12% at the terminals zones in some scenarios. On the other hand, this approach may be relatively challenging due to financial, physical and regulatory limitations, yet building a general awareness towards better efficiencies may contribute to risk reductions coupled with other economic and environmental benefits.

A pertinent use of the simulation based risk model is achieved through the analysis of vessel prioritization during resumption of trade after a possible disruption such as an accident, a terrorist attack or a natural disaster. As outlined in SAFE Port Act of 2006 and identified by Department of Homeland Security's strategy report of 2007, the prioritization of vessels is a critical part of risk management approach to incident response. There are multiple goals throughout this process such as minimizing safety/security risks and minimizing the economic impacts. Thus, the entire problem is a complicated multi-objective decision problem. In this regard, the issue of vessel prioritization is studied through a hypothetical incident similar to the case of Athos I, happened in Paulsboro in November of 2004. The simulation based risk model is employed for estimating the performance as well as risk measures.

Various scenarios are considered focusing on port closure policies as well as reopening strategies on admitting vessels into the river based on prioritization schemes and pursuit distances to control vessel proximities. Several measures are defined to evaluate port performance and risk implications. The results indicate that closure policies such as complete or partial closure of the system have the most influence on port and risk performance. Prioritization is a significant control for reducing the waiting time of targeted vessels, however at the expense of slight risk increases as in the instance of tankers. Pursuit distance is a strong control to mitigate risks, yet conservative policies may cause excessive number of vessels waiting in the queues. The analysis demonstrates vessel priorities, when combined with appropriate pursuit distances, constitute variables for effective resumption of trade. However, such policies require incisive planning and coordination among agencies, and preparation of protocols clearly defining appropriate roles especially on the final authority over vessel prioritization.

Finally, modeling vessel arrivals at ports and waterways are studied due to their major effect on the accurate estimation of port and risk performance measures. The appropriate modeling of input processes often requires correlation to be taken into account for developing realistic simulation models. General purpose methods for representing and generating dependent arrival processes in simulations are scarce in literature. Even available models have their deficiencies such as generating negative values, thus making them not appropriate for use in simulations or they do not capture both distribution and correlation properties.

In reference to real life practice at ports and waterways, one-dimensional point processes is used to model vessel arrivals at terminals in simulation models. This semi-scheduling process is modified and improved through introducing new parameters, and shown to produce better feasible region to capture both variation and correlation properties. A computer program is developed to estimate all the parameters for the modified model to produce the targeted variation and the first lag correlation. It is shown that higher order correlations can also be produced through introducing new parameters to the model.

In this research, several practical and analytical aspects of vessel traffic in ports and waterways are studied. The models and approaches developed throughout this dissertation revolve around Delaware River and Bay, however, the general problem domain and all the issues considered are common to other port and waterway systems. Thus, one of the objectives of this dissertation is to provide guidelines to similar studies.

The methodology developed based on a mathematical risk model integrated with a simulation model is a practical contribution of this work. On the other hand, all the numerical experiments provide empirical contributions to decision making processes especially for Delaware River and also possibly for other port systems. At last, the proposed model for semi-scheduled arrivals (the modified process of scheduled arrivals with lay period) is an analytical contribution for the modeling of correlated input processes in simulations.

The simulation model integrated with the risk model itself, developed for Delaware River and Bay as a decision support tool, is another product of this research. The model is a realistic representation of the port system with all the vessel traffic and terminals, and enables experimentation with policies, operating procedures, decision rules or environmental changes. Thus, it can be used to support decision making process to evaluate risks and performance. In addition, with modification it can be used in various areas of interest such as to examine feasibility and the effects of port expansion projects or new infrastructure facilities, as well as effects of vessel traffic on natural life such as fisheries.

Several future study topics can be deduced from this research on top of several improvement ideas outlined in each chapter. A couple of them are summarized below.

For the simulation and risk modeling, inclusion of other possible factors affecting the vessel traffic can be investigated. Some factors that are found not relevant or impractical in this study can be appropriate for other systems. Vessel reliability, local traffic, wind and visibility conditions or implementation of vessel scheduling algorithms can be a few of them.

Assessment of risks is dependent on historical data in this study. This may provide insights, and assuming the future will be as history indicates, one may obtain good predictions of risks for the future. However, as Aven (2010) points out, there is critical need to look beyond historical data since risk is about surprises to a large extent. In this respect, a future research area could be implementation of predictive models to the risk analysis approach. Risk analysis in port security context is also growing in recent years. A simulation based risk analysis approach can also be used in port security especially in implementing possible scenarios and estimating regional and economic impacts of these scenarios.

The simulation model developed in this research evaluates each vessel's individual impact on the overall risk in the river. This idea can also be used in the real time vessel management services. In a similar manner risks are tracked in the simulation model as it runs, risks could be tracked in a waterway system with the use of automatic identification systems (AIS). An important idea developed throughout this research is the possibility of integration of a similar mathematical risk model fed by data flow through AIS. This way, real-time risks in a waterway system can be tracked. Integrating such real-time risk tracking systems into vessel traffic services (VTS) can assist to provide better navigational safety in critical ports and waterways.

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### PUBLICATIONS

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