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EXECUTIVE SUMMARY

The work presented here was carried out as a Maritime Security Center project. A modeling and simulation-based framework has been developed for predicting the consequences of disruption at ports in a region due to the passage of a hurricane event. This research seeks to expand understanding of port resiliency and enhance the knowledge in the development of a stakeholder-focused tool to improve regional resilience. The tool uses modeling and simulation to predict consequences of disruptions at regional ports due to a hurricane event, in support of seeking improvements in the regional preparedness of ports. The effort is based in particular on adapting archival Nationwide Automatic Identification System (NAIS) and Department of Transportation (DOT) data for resilience analyses of the coastal ports affected by Hurricane Matthew, a category 5 Atlantic hurricane that skirted the southeast US coast in October, 2016. Port operations leading up to Hurricane Matthew and observed losses in system functionality during and following the storm are used to quantify the impact on six case-study ports using time dependent performance analysis. Modeling and simulation involve first modeling the port systems on a VISSIM software platform and establishing baselines for normal port operations on the waterside and landside in the southeast region, based on archived statistics. Impacts of Hurricane Matthew on the six case-study ports (Port of Miami, FL; Port Everglades, FL; Port of Jacksonville, FL; Port Canaveral, FL; Port of Savannah, GA; Port of Charleston, SC) are considered. Baseline operations are established in terms of port service and throughput at these ports. Simulations of baseline vessel operations are conducted using the Monte Carlo simulation approach of Inverse Transform Sampling. Once the baseline models are established, disruption due to Hurricane Matthew is simulated to determine the consequences of the disruption. The predictions are compared with available observed data for the event. The tool has the following primary benefits: 1) Improvements made using the tool for hurricane preparedness, planning and COOP at ports will lead to reduction in vulnerability of ports to hurricane events; 2) Prediction of consequences of disruption at regional ports due to a hurricane event, validated with actual impact of Hurricane Matthew, will lead to reduction in uncertainty of the impact of such an event; and 3) Capability to predict and compare consequences resulting from various responses to a hurricane event will lead to better decision-making in responding to a hurricane event. A kick-off meeting with the U.S. Coast Guard (USCG) was held on 7/19/2018 to determine the project’s scope, deliverables, and the case study ports. The options for tool transition were discussed and housing the tool in USDOT’s Freight Mobility Research Institute at FAU where it would be made available to stakeholders was chosen as the preferred option. Additional stakeholder engagement included a well-attended stakeholder workshop at FAU on March 29, 2019, periodic conference call discussions with USCG personnel and visits to ports. The engagement with the USCG, Department of Homeland Security (DHS) Centers of Excellence (COE), and Port Authorities helped in the identification of the best-fitted data for the project. Additionally, data on ship and ground vehicle movements were obtained from the DOT and on vessel movement from Marine Traffic Online. The acquired data have been used to model the six case-study ports and their baseline operations. The six ports were modeled, incorporating consideration of ship movements during normal port conditions. All baseline data for a 30-day window encompassing Hurricane-Matthew event were incorporated into the models and the VISSIM platform. A hybrid model that connects the waterside and landside activities has been established. Calibration and validation of the model has been carried out. There are 5 sets of baseline data for every port, totaling 30 simulations in order to calibrate and validate the models. Once the models were calibrated and validated, disruptive case scenario, based on Hurricane
Matthew was analyzed and compared with actual observations during the event. Two scenarios were considered, one with the ports operating at normal capacity to clear the backlogs following port closure, and the other with the ports operating with enhanced capacity. The impact on containerized vessels in the region was quantified in terms of lost vessel hours and associated financial impact.

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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>AADT</td>
<td>Average Annual Daily Traffic</td>
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<tr>
<td>BRIC</td>
<td>Baseline Resilience Indicator for Communities</td>
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<td>CDF</td>
<td>Cumulative Distribution Function</td>
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<tr>
<td>COE</td>
<td>Center of Excellence</td>
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<td>CREATE</td>
<td>Center for Risk and Economic Analysis of Terrorism Events</td>
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<tr>
<td>DHS</td>
<td>Department of Homeland Security</td>
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<td>DOT</td>
<td>Department of Transportation</td>
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<td>FAU</td>
<td>Florida Atlantic University</td>
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<td>FECR</td>
<td>Florida East Coast Railway</td>
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<td>FY</td>
<td>Fiscal Year</td>
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<td>GA</td>
<td>Georgia</td>
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<td>JAXPORT</td>
<td>Port of Jacksonville</td>
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<td>JOC</td>
<td>Journal of Commerce</td>
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<tr>
<td>ICTF</td>
<td>Intermodal Container Transfer Facility</td>
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<tr>
<td>LLC</td>
<td>Limited Liability Company</td>
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<tr>
<td>LNG</td>
<td>Liquefied Natural Gas</td>
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<tr>
<td>MARS</td>
<td>Methodology for Assessing Resilience for Seaports</td>
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<tr>
<td>MIT</td>
<td>Massachusetts Institute of Technology</td>
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<tr>
<td>MSC</td>
<td>Mediterranean Shipping Company</td>
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<tr>
<td>NAIS</td>
<td>Nationwide Automatic Identification System</td>
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<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
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<tr>
<td>NSF</td>
<td>National Science Foundation</td>
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<tr>
<td>PANYNJ</td>
<td>Port Authority of New York and New Jersey</td>
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<tr>
<td>PDF</td>
<td>Probability Distribution Function</td>
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<tr>
<td>PIERS</td>
<td>Port Import Export Reporting Service</td>
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<tr>
<td>PortSec</td>
<td>Port Security Risk and Resource Management System</td>
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<tr>
<td>RBC</td>
<td>Ring Barrier Controller</td>
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<tr>
<td>RIPS</td>
<td>Resilient Interdependent Infrastructure Processes and Systems</td>
</tr>
<tr>
<td>RoRo</td>
<td>Roll-on / Roll-off</td>
</tr>
<tr>
<td>SC</td>
<td>South Carolina</td>
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<tr>
<td>TEU</td>
<td>Twenty-foot Equivalent Unit</td>
</tr>
<tr>
<td>UK</td>
<td>United Kingdom</td>
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<td>US</td>
<td>United States</td>
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1.0 INTRODUCTION

Ports are a vital part of the infrastructure for many nations. In 2014, seaports contributed to 26 percent of the United States’ $17.4 trillion economy. Ports help to deliver essential goods including food and gasoline to major distribution hubs to be sent throughout the country. US Ports employ 23.1 million people and contributes $1.1 trillion dollars to personal wages and local consumption (American Association of Port Authorities, 2015). In the United States there are 29 ports on the West Coast and 16 between the East Coast and the Gulf of Mexico (Welshans, 2015). Ten metropolitan ports across the country account for 60 percent of international goods arriving in the country by sea, air, and road (Tomer & Kane, 2015).

US ports and container/intermodal terminals are critical links in the marine transportation system. Disruption at a port can have a crippling economic effect in the coastal zone as well as the rest of the nation. Ports are vulnerable to natural disasters since they are fixed, publicly accessible entities. Port stakeholders have a vested interest in the long-term function and viability of ports, but no standardized measures for performance or resilience exist for regional ports. In the last 26 years, sea levels have risen 2.6 inches (NOAA, 2008). With rising sea levels, major hurricanes (category three or higher) in the Atlantic have increased 74 percent (NOAA, 2015). The increase in major storms has made the need for resilient marine transportation systems even more vital. The proximity of ports to other major bodies is affected by storm surge and changing currents and tides. Since ports are such a vital part of the economy, they are potential targets for those seeking to do harm. In addition to the economic impact that a port disruption would cause, the environmental effects that could occur within the waters would also threaten the local ecology. Ports that service interconnected channels can also form queues and hinder access to upstream facilities. This can have a major impact on capacity and the overall level of service provided by the port system.

Hurricanes, oil spills, and labor disputes can all be sources of port disruptions. Hurricane Sandy in October 2012 closed the Port of New York/New Jersey for over a week from full operation. The hurricane caused flooding, loss of power, and damages to the port that prevented the ports from reopening immediately. It was estimated by the Port Authority of New York and New Jersey (PANYNJ) that the port closure cost $170 million (Smythe, 2013). Between the time the port partially reopened (three days after landfall) and the time the port returned to full operation (eight days after landfall), dwell times of vessels trying to enter the port climbed as high as 50 hours (Wolshon, Parr, Farhadi, & Mitchell, 2018).

In September 2017, Hurricane Maria closed the Port of San Juan for three days until 11 cargo ships were allowed to enter with supplies for the devastated island. Eight days after the initial closing 10,000 shipping containers remained stranded in the port unable to navigate the island due to the damage to the island’s infrastructure making the roadway network impassible for truck drivers to arrive at the port and for the trucks to leave the port to deliver the supplies. (Gillespie, Romo, & Santana, 2017).

A labor dispute at the Port of Long Beach Labor affected 29 ports along the West Coast of the United States and cost $7 billion in 2015. Labor disputes that close ports can cripple an economy that shipped 240 million tons of goods in 2013 alone (DePillis, 2015). As the number and size of ships increase, the processing time of goods in the ports decreases. Containers from
Asia remained anchored outside the port for 10 days before they could enter and unload (Welshans, 2015). Even after the port reopened to normal operations it took several days to return to normal operating level of service. Traffic congestion also affects ports. In 2014 truck drivers waited four hours to pick up a container to transport from the port (DePillis, 2015).

In March 2014, the Galveston Bay port was closed when 168,000 gallons of fuel spilled following a collision of a tank-barge with a long bulk carrier. The fuel spill forced the port to close for cleanup and resulted in a large queue of vessels waiting to enter the port for four days. Dwell times during the port’s closure exceeded 120 hours (Wolshon et al., 2018). In May 2019, another oil spill occurred in the Houston Ship Channel depositing 9,000 gallons into the waterway. The Houston Ship Channel is a “lifeline to the Gulf of Mexico and the foreign markets” (Cunningham, 2019). Its closure to allow for cleanup had major implications for the port industry in the area for both incidents.

The National Science Foundation (NSF) defines resiliency as “the ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events” (Resilient Interdependent Infrastructure Processes and Systems (RIPS), 2006). Resilient infrastructure is more than clearing debris from roadways after a storm, it is providing the means to deliver the essential goods and supplies needed to safely and quickly recover from a storm, attack, or other major disruption. Resilient ports will help to create a shorter disruptive period and a faster time to recovery of the physical infrastructure and economic livelihood of the ports. There is an evident need to better understand the relationship between port operations, disruptions, and resiliency on both a local and regional level.

1.2 Research Goal, Objectives, and Broader Impact

An approach to measuring resilience must be adaptable to the specific needs of the community using it, which quickly renders a national-scale resilience metric nearly impossible. Driven by global economic forces, ports have unique needs that should inform indicators to assess resilience over time. Quantitative methods and tools, stemming from engineering science and vulnerability studies, provide quick assessments of “resilience” at broad spatial scales, but do not dip below the surface into local scale, place-based, community resilience. Qualitative methods, on the other hand, help answer research questions that cannot be addressed with numerical data and dive into questions of attitude, perception, and social interaction.

The goal of this research is to demonstrate the utility of a predictive port resiliency assessment tool. The developed tool involves VISSIM based hybrid multimodal simulation that analyzes port operations and provides a quantifiable assessment of local and regional resiliency. VISSIM is a state-of-the-art microscopic transportation simulation model commercially developed by VISION. The application of this tool is shown on six ports in the Southeast US. The waterside port simulation models have been developed using vessel Automatic Identification System (AIS) data and programmed within a VISSIM simulation of landside operations. This hybrid modeling approach is used to visualize vessels and allows them to interact in both time and space with each other and landside port infrastructure. VISSIM also provides a means of analyzing vessel queuing and data extraction. Local and regional resiliency is quantified through the analysis of time-dependent resiliency plots and used as a performance measure in this study. The utility of the predictive port resiliency assessment is demonstrated in response to Hurricane
Matthew. However, the novel procedure described here can be applied to any local or regional port hazard.

This research has expanded the understanding of port resiliency and enhanced the knowledge in the development of a stakeholder-focused tool to improve regional resiliency. This research used knowledge, innovation, and education, as well as modeling and simulation, in support of assessment of port resiliency. Given the nature of resilience as a dynamic process, this study considered strategies for managing identified risk. The approach used allows assessment of port resilience and improvement in understanding of the consequences of hurricane events at the ports and the intermodal facilities in a region, in support of seeking improvements in the regional preparedness of interconnected port systems. The application of the predicitve port resiliency assessment tool can lead to more informed decision making for emergency managers and port officials. Ideally, the developed tool will be used to evaluate objectively the resiliency of local and regional ports in response to policy, protective actions decisions, and infrastructure improvements. The dynamic simulation architecture allows for the evaluation of various hazards, timescales, and regions. Port planners may also find this tool useful to demonstrate the benefits of investment on resiliency using a quantifiable metrics.

The end-user stakeholders were engaged early to develop requirements for the tool, gather available data and identify points-of-contract for obtaining feedback during the course of the project. The data was obtained from state departments of transportation and online data procurement resources. In conjunction with port authorities, US Coast Guard, DHS Centers of Excellence (COE) and other stakeholders, the scope and the requirements for the methodology was defined. Requirements to successfully quantify resiliency of the port system from a major hurricane event and rate of recovery from it will include the following:

(i) Assessment of the level of threat
(ii) Assessment of vulnerabilities of the port system
(iii) Determination of standard operating procedure in response to a disruptive event

The completed tool has the following attributes:

(i) Provide means to reduce risk
(ii) Identify, assess, and monitor disaster risks and improve early warning systems
(iii) Build a culture of safety and resiliency at all levels through the use of knowledge, innovation, and education
(iv) Reduce consequences from underlying risk factors
(v) Improve disaster preparedness of ports and its water and landside capacity distribution
(vi) Speed the post-disaster recover
(vii) Facilitate coordination of resumption of commercial service and relief activities
(viii) Improve interagency coordination and communication

The following section of this report highlights the relevant prior literature in the areas of port resiliency and modeling. This is followed by a description of stakeholder engagement and a description of the six ports used as part of the regional case study. The modeling and resiliency
assessment methodology is then presented followed by the analysis, results, and discussion and conclusions.

2.0 LITERATURE REVIEW

A number of research efforts underway have focused on the resiliency of coastal infrastructure as well as the transportation network. These include DHS funded work at the Critical Infrastructure Resilience Institute (CIRI), CREATE COE, and the Coastal Resilience Center (University of North Carolina-Chapel Hill), decision-support tools for flood risks at RAND Institute; as well as lessons learned from previous storm events such as Hurricane Sandy. This tool builds on and is complementary to these research efforts.

2.1 US Coast Guard Instructions

The United States Coast Guard (USCG) has well defined Pre and Post-Storm instructions for a major weather event on the Eastern Seaboard of the country, they are outlined below. The Coast Guard’s top priority is the safety of life during all recovery operations.

The USCG Pre-Storm instruction consists of 4 different hurricane conditions (Whiskey, X-Ray, Yankee, and Zulu). First, Whiskey consists of the first 72 hours of the weather event, where the Coast Guard conducts port surveys and implements containers stacking protocols. Second, X-Ray is within 48 hours, where all ocean-going vessels over 500 GT are required to depart port and a “remaining in-port plan” must be submitted to the Coast Guard if the vessels are unable to depart. The Yankee condition takes place within 24 hours of the weather event, which closes the port to all inbound traffic, all-cargo operations. Additionally, drawbridges may cease operation within 8 hours of the predicted tropical winds. The last condition is Zulu which occurs 12 hours prior and throughout the duration of the weather event. This last condition suspends all port waterfront operations and both (port and waterfront) facilities remain closed until the passage of the storm.

The USCG post-storm plan involves meeting and verifying several conditions prior to the port opening. The following five conditions must be met, at the bare minimum, prior to the port opening. The first condition involves conducting a damage assessment to ports and waterways completed in conjunction with the Army Corps. The second condition is the verification of the correct location of the aids to navigation. The third condition is checking the status and conditions of all drawbridges. The fourth condition is the re-establishment of required port security measures in accordance with respective port security plans; it involves Customs and Border Protection to be ready to process all cargo and personnel. The fifth condition requires the evaluation of oil spills or hazardous material release in the port area and to identify the potential sources.

Depending on the severity of the weather event, the Captain of the Port may issue Captain of the Port Orders called a “Soft” Port Opening. This soft port opening may consist of the following restrictions depending on the damage to the port. They may establish safety zones or restrict transits to “daylight only” and additionally may require additional tug escorts.

2.2 Resiliency Assessment
Adam Rose and Shy-Yi Liao (2005) address regional resilience towards disasters in their paper “Modeling Regional Economic Resilience to Disasters: A Computable General Equilibrium Analysis of Water Service Disruptions”. They utilize the computable general equilibrium modeling approach in order to estimate the regional economic impacts of earthquakes and other disasters that can cause supply chain disruptions. Some of the main functions of this model included operational definitions of individual and regional resilience, identification of production function parameters and development of the algorithms for recalibrating production functions to data.

In addition, Mo Mansouri, Roshanak Nilchiani and Alsi Mostashari (2011) conducted a research project titled “A Policy Making Framework for Resilient Port Infrastructure Systems”. In their work they developed a Risk Management-based Decision Analysis framework, with the goal of forming a systematic process for making strategic and investment decisions in case of disruptions. The disruption cases considered ranged from natural disasters, to organizational, technological and human factors. Their approach can help to identify common elements of uncertainty in port systems, evaluate the costs incurred with various potential failures and with investing in resilience strategies.

In their article titled, “Resilience Framework for Ports and Other Intermodal Components,” Rahul Nair, Hakob Avetisyan and Elise Miller-Hooks (2011) discuss ports and intermodal freight systems, highlighting the dangers that hinder cargo transportation and the infrastructure’s vulnerability to disasters. They quantify resilience as the post disruption fraction of demand that can be satisfied while using specific available resources and managing to maintain a prescribed level of service. Additionally, they employ their concept on a system level and propose a generic framework for its application in intermodal facilities. In another article, Elise Miller-Hooks, along with Xiaodong Zhang and Reza Faturechi (Miller-Hooks and Faturechi, 2012) conducted another research study related to resilience named “Measuring and Maximizing Resilience of Freight Transportation Networks”. Their model, apart from measuring resilience levels of a freight network, includes optimal setting of actions and allocation of budget between preparedness and recovery activities under level-of-service constraints.

The National Center for Risk and Economic Analysis of Terrorism Events at the University of Southern California spearheaded a project titled “PortSec: Port Security Risk and Resource Management System” (Orosz, 2011). Its objective was to create a system for risk assessment and security resource allocation for various dangers that hinder seaport operations. This decision matrix is used by the port authorities to manage and balance the increasing safety restrictions. This matrix allows the Port Authorities to maximize business throughput and minimize environmental impacts. The project has two main uses, strategic and tactical. Strategic usage includes the creation of tools for evaluation of the cost-benefit by adding/modifying new port counter-measures. On the other hand, the tactical usage of the tool provides up-to-date risk assessment for both identified areas of interest and for the overall port complex.

The Center for Transportation & Logistics at the Massachusetts Institute of Technology (MIT) conducted a multi-year Port Resilience project (Rice and Trepte, 2013). The goal of the study was to estimate the capacity required to absorb various failures of United States ports. The project included a port capacity analysis, port failure mode analysis and a detailed port resilience survey. In addition, they developed a platform called MIT Port Mapper, which is designed to identify U.S. ports that can potentially absorb cargo in the event of a port disruption. The user
chooses the state he wishes to examine and either all or a portion of the state’s ports. In addition, the platform is used for gathering information on the type of materials handled in each port (e.g. radioactive, containers); the data in the platform was obtained from the Army Corps of Engineers.

Moreover, the Americas Relief Team (2013) in collaboration with FedEx conducted a project titled “Port Resiliency Program.” Its objective was the preparation of airports and seaports in the Caribbean and Latin America to be more resilient in the face of natural disasters by applying lessons learned in Hurricane Katrina and the Haiti earthquake. Their approach for achieving their goal comprised of three main steps: Initial self-assessment by the airport or seaport; planning of a workshop in Miami to identify gaps and training needs in sea and air port operations; and a site visit to present targeted training and a tabletop exercise to assess the preparedness of the airport or seaport.

A study conducted by Tiffany C. Smythe (2013), from the Center for Maritime Policy and Strategy of the U.S. Coast Guard Academy, titled “Assessing the Impacts of Hurricane Sandy on the Port of New York and New Jersey’s Maritime Responders and Response Infrastructure,” focused on Hurricane Sandy. The goal of the study was to identify “lessons learned” from this hurricane, in order to educate the maritime community in the necessary actions required to mitigate impact during future storm events. The methodology used for achieving the goal included three main steps: meetings with the U.S. Coast Guard, data collection via participation in meetings and semi-structured interviews with key informants, and qualitative data analysis of the interview content. In addition, the research aimed to lay the groundwork for larger-scale and longer-term studies related to coastal storms and port resilience planning.

Other qualitative analyses of port disruptions due to hurricanes have been undertaken to study stakeholder perceptions (Becker, Matson, Fischer, & Mastrandrea, 2015). This article proposed a storm impact typology for two ports (Gulfport, Mississippi and Providence, Rhode Island) to include direct damages, indirect costs, and intangible consequences. The authors found that formal planning did not address many stakeholder concerns, particularly the impacts of intangible consequences that are borne by a large number of stakeholders and society at large.

In addition, an important area of research in the field of port resilience deals with the identification of the costs associated with port disruptions. Adam Rose and Dan Wei (2013), in their paper called “Estimating the Economic Consequences of a Port Shutdown: The Special Role of Resilience” address this matter. They developed a demand and supply-driven methodology that takes into account imports, exports and the major types of resilience in terms of alternative options. The study was successful in developing a tool to estimate the total economic consequences of a seaport disruption. After applying their approach to a 90-day disruption at the seaports of Beaumont and Port Arthur, Texas, they concluded that a carefully thought-out resilience plan can reduce the impacts of disruption by as much as 70%.

Studies regarding port resilience have also been conducted outside the U.S. An example is a paper from Andrew Grainger and Kamal Achuthan (2014) from the University of Nottingham, as part of a collaborative project with the United Kingdom Department of Transport, titled “Port Resilience: a Primer”. The study focused on the importance of U.K. ports, various vulnerability
issues often encountered in them, preparedness methods followed to address those problems and various actions that can be taken in order to improve port resilience. Some of these actions include the development and adoption of strict planning and business continuity standards, development of simulation tools that can help understand and predict specific events taking place and identification of incentive mechanisms to ensure stakeholder interests towards resilience.

Hui Shan Loh and Vinh Van Thai (2014) in their paper “Managing Port-Related Supply Chain Disruptions: A Conceptual Paper” focused on the management side of port resiliency. They developed a management model that addresses a full set of operational risks from a holistic perspective, and in connection with various supply chain disruptions. Therefore, their model identifies the necessary actions taken from ports in order to minimize port-related supply chain disruptions. The proposed approach incorporates the theories of risk, quality and business continuity management in order to make decisions in the institutional bearings, management policies and operations actions related to port disruptions.

Moreover, a journal paper that deals with the quantification of resilience was authored by Raghav Pant, Kash Barker, Jose Emmanuel Ramirez-Marque, Claudio M. Rocco (2014) and titled “Stochastic measures of resilience and their application to container terminals”. In their work they modeled the system resilience as a function of both vulnerability and recoverability, while also incorporating aspects of stochasticity and uncertainty in terms such as time to total system restoration and time to full system service resilience. The resiliency decision making framework created includes commodity flows at a port, full or partial terminal closures due to disruptive events and restoration activities and was applied in a case study at the port of Catoosa in Oklahoma.

The National Cooperative Freight Research Program of the Transportation Research Board developed a large project called “Making U.S. Ports Resilient as Part of Extended Intermodal Supply Chains” (Southworth, Hayes, McLeod, & Strauss-Wieder, 2014). The main project tasks first included a thorough literature review on past disruption events that affected port operations, emphasizing the actions taken to tackle the problem and limit the extent of the disruption. Next, interviews with port operations, truck, rail, and ocean vessel carriers were conducted in order to understand their opinions on current levels of port resiliency, as well as on what are the best means of enhancing resiliency and speeding recovery should a disruption occur. Later, two detailed case studies of port disruptions were developed, the impacts of the superstorm Sandy’s on the major East Coast ports and the extended lock closures along the Columbia River System in the Pacific Northwest. Last, the team developed guidelines suitable for public-sector decision makers who might become involved in a disruption recovery event.

An interesting project was conducted by the Stevens Institute of Technology, and funded from University Transportation Research Center, Region II, with the title “Port Resilience: Overcoming Threats to Maritime Infrastructure and Operations from Climate Change”. The study states that the growing concerns about climate change and severe weather events occurring has transformed the area of port and coastal resilience into an important component in operations planning. The principal objective of the project is the creation of a standardized framework for the improvement of resilience in ports and transportation systems, via the integration of physical infrastructure and social systems. Stakeholder interviews, and workshops were organized that
improved social awareness and identified the most important problems encountered while dealing with disruptions. Some of the solutions identified was the implementation of strict design standards, the organization of the transport systems as a whole, in terms of the entire supply chain, and to look beyond local operations. Last, the project suggested a coordinated organizational scheme at the state and regional level that can assist in the interaction towards the landside operations and water side logistics teams throughout the whole disruption cycle.

Another project with significant value to the problem addressed in our study was conducted from the Centre for Transport Studies of the University College London (Achuthan et al., 2015), titled “Resilience of the Food Supply to Port Flooding on East Coast”. The study argues that since the UK imports more than 40% of its food and drink supplies, with most of it arriving by sea, it is of utmost importance for port systems to be able and adopt good resilience plans. The methodology followed in the project consisted of engagement with stakeholders, modelling and analysis of the UK ports and shipping import functions, and the development of disruption scenarios using simulation. Some of the key findings extracted from the project were the degree of the disruption at a port would vary according to the food type moved and the shipment method, and that rerouting RoRo and container vessels to other available ports can potentially reduce the impacts of the event to almost half.

Furthermore, the Gulf of Mexico Alliance (Morris, 2016) conducted a study named “Ports Resilience Index: Three Case Studies in the Gulf of Mexico”. The objective of the project is the production of a simple and easily implementable regional tool that port and marine transportation authorities can use to evaluate and assess their level of resilience, as well as predict their ability to achieve an acceptable level of service during and after major weather events. The Ports Resilience Index is constructed using the Delphi Method, commonly used for quantifying variables of uncertainty and reaching a statistical consensus. The case studies considered were the Port of Corpus Christi in Texas, the Port of Pascagoula in Mississippi and the Port of Lake Charles in Louisiana.

A research paper from Justice et al. (2016), named “US Container Port Resilience in a Complex and Dynamic World” addressed the problem of how container ports in the U.S. can potentially be affected by various negative events and how they can implement resilience practices to counteract the issues. The authors emphasized the importance of resilience as a way of dealing with uncertainties, while also mentioning that due to these potential changes, the ‘business as usual’ approach adopted by most organizations may not be able to guarantee successful port operations. Last, they state that in order to manage and encompass resilience, innovative and creative methods are required.

Hong Chen, Kevin Cullinane and Nan Liu (2017) also dealt with the subject of measuring resilience in transportation networks, in their paper titled “Developing a Model for Measuring the Resilience of a Port-Hinterland Container Transportation Network”. In their study, after developing their own definition of resilience in transportation networks and port operations, they developed a model to quantify resilience while incorporating links, nodes, cost, time and port capacity from the perspective of shippers. They considered a single seaport in their model and applied their methodology to the Gothenburg port and part of its hinterland.
Hyungmin Cho and Heekyung Park (2017), co-authored a paper titled “Constructing Resilience Model of Port Infrastructure Based on System Dynamics”, creating another study that focused on building resilience models of ports. In their work, they state that since port infrastructure and operations are complex processes and difficult to analyze all their components, a systemic approach can prove efficient. Their system dynamics model incorporates the cargo process as its performance level and identifies the elements corresponding to various resilience attributes. Additionally, the model includes factors such as changes in cargo volumes and financial states, and with the application of different disruption scenarios, is used as a method of comparing the resilience levels of port infrastructure.

A relevant work that focused on the impacts of hurricanes in port operations was conducted by Touzinsky et al. (2018), titled “Using Empirical Data to Quantify Port Resilience: Hurricane Matthew and the Southeastern Seaboard”. In their study they used Automatic Identification System based vessel arrival data on three case study ports hit by hurricane Matthew, Charleston, Savannah and Jacksonville. Their goal was to calculate cumulative dwell times and net vessel counts in order to simulate and quantify the behavior of the system during all the main stages of the hurricane. These stages included pre-storm, preparedness, resistance, recovery and post-storm. In each stage, they used Bayesian analysis for understanding the system performance variations over the whole hurricane incident time.

2.3 Port Modeling

Port modelling takes on multiple aspects to obtain the most realistic model of the area. Since ports are a transfer point for cargo, they have unique characteristics and can be affected by both the landside and seaside of the operation by disruptions. Ports are a large part of the economy requiring them to be resilient in the face of disruption to continue to provide for the country. The National Science Foundation (NSF) defines resiliency as “the ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events” (Resilient Interdependent Infrastructure Processes and Systems (RIPS), 2006).

According to John, Yang, Riahi, and Wang, “when critical maritime systems do not have the robustness to recover in the face of disruption, they present themselves as attractive targets to terrorism-related attacks” and “disruptions at any point within their operation could potentially result in catastrophic and disastrous consequences” (John et al., 2015). Alyami, Yang, Riahi, Bonsall, and Wang agreed that resiliency is important because “safe and reliable operations are of great significance for the protection of human life and health, the environment, and the economy” and early detection of hazards is crucial in avoiding performance degradation and damage to human life and property” (Alyami et al., 2016).

Mangan, Lalwani, and Gardner (2002) point out that reliability has been highly ranked in port choice by many researchers. Murphy and Hall ranked it as the number one most important variable in predictive port modeling in 1995 and Cullinane and Toy ranked it as number three in 2000 (Mangan, Lalwani, and Gardner, 2002). While reliability and resiliency are conceptually different, they can result in similar outcomes. Ports must be reliable in their ability to operate prior to, during, and following adverse conditions; therefore, being resilient.
Magala and Sammons state the “in a highly competitive and rapidly globalizing economy of today, the integration of supply chains is taking pace and ports are increasingly competing not as individual firms but rather as firms within supply chains” (Magala and Sammons, 2008). This is an important aspect of port modelling because when modelling a port just the movements alone within the port cannot be solely examined, but the interaction with the vessels offshore and the rail or trucks used to move the cargo from the port to its destination. Magala and Sammons reasoned that by modeling them as “an integrated supply chain the opportunity to reduce vulnerability to competition by providing the port with complementary resources and capabilities needed to compete more effectively in the marketplace” (Magala and Sammons, 2008).

According to Al-Deek, “seaports are primary generators of freight traffic, both truck and rail (Al-Deek, 2001). This supports ideas stated by Magala and Sammons that when modelling a port the entire system must be examined. Al-Deek states that the trip generation and modal split aspects of the “four-step transportation planning process” must still be done to relate the number of truck and rail trips generated by the vessels (Al-Deek, 2001). Traffic movements within a port can be as high as 2000 per day and the number is expected to continue to increase (Debnath, Chin, Haque, 2011). With such a high number of traffic movements “terminals must have the facilities to provide adequate level of service” (Kozan, 1996).

Le Tixerant, Le Guyader, Gourmelon, and Queffèlec note that this in a “multiplying, diversifying, and intensifying sea-related use” and with that an “increase in traffic linked to maritime shipping” and other activities (Le Tixerant et al., 2018). Due to the ever-changing nature of ports the variability in delays must be examined when modeling ports since level of service is dependent on it (Kozan, 1996). AIS (Automated Identification Systems) can be used to help model ports by allowing for classifying vessel patterns (Chen, Xue, Wu, Qin, Liu, & Chen, 2018).

Kozan and Preston acknowledge that the arrival time of a vessel to the port, also known as the berthing time, “accounts for a considerable portion of the journey;” therefore, it is an important aspect to be included in port modelling (Kozan and Preston, 2006). Due to the complexity of ports and “the dynamic nature of the environment, a large number of timely decisions have to be continuously reviewed in accordance with the changing conditions of the system” (Kozan and Preston, 2006). As vessels enter a port they are received until full capacity and with minimum queuing time that is determined using the average waiting time, optimum number of berths, and the maximum numbers of ship waiting to enter (Costea, Ticu, & Mishkoy, 2019).

Howard, Bragen, Burke, and Love discuss the need for a port to be able to “deploy an armed cavalry division through the port, given a specified allocation of port resources (Howard, Bragen, Burke, and Love, 2004). Howard et al. used PORTSIM 5 to model this and to help “identify ports for which additional infrastructure (newly constructed or lease from the port) can speed the process of deployment” (Howard et. al, 2004). This is important when examining the resiliency of ports and what is available prior to and following an event.

Vessel Traffic Service (VTS) uses vessel movements to predict movement on waterways through “collection, verification, organization and dissemination of information” (U.S. Coast Guard, 2018). VTS is important in port modeling because it helps to identify vessels that have
navigation limitations that may need assistance to enter the port. Vessels needing assistance affect the operations of ports greatly. Vessel navigation behavior determined by VTS is compared to existing port models that allow for demand to be examined within the port (Olba, Daamen, Vellinga, & Hoogendoorn, 2018). VTS allows for more accurate port modeling by helping to determine if vessels abide by the International Maritime Organization (IMO) movement rules within the ports or if the follow different and often dangerous paths that would increase risk and decrease safety (Olba et al., 2018).

3.0 STAKEHOLDER ENGAGEMENT AND CASE STUDY PORTS

US Coast Guard, DHS COEs, and Port Authorities are the primary stakeholders when responding to natural disasters and port operations. These stakeholders were engaged with throughout the research process and helped in the identification of the study areas, data requirements, project scope, and deliverables. A series of interviews, meetings with stakeholders, and workshops were held with stakeholders to guide the project beginning with a kick-off meeting and combination in the submission of the final report.

Meetings with officials from DHS and the US Coast Guard were held in order to determine the scope of the project and its benefits for the stakeholder purposes. These meetings helped form a better view of the problem and the needs of the stakeholders so that the results of the research will be useful in making port operations more efficient during an emergency event. Further information about the operations of the case studies was collected through meetings with the Port Managers of each port and visits to ports.

On March 29, 2019, major stakeholders with interest in infrastructure resilience and impacts convened for our Supply Chain Sustainability and Transportation Resilience workshop, in Dania Beach, Florida. This workshop focused on both supply chain sustainability and transportation resilience, with a wide range of presentations, that spun from framework proposals to transportation and operations management-based research. Acknowledging the breadth of issues faced by ports and the communities they affect. The port stakeholders’ workshop in resilience built on outcomes for two theme-based listening sessions and collaboratively explored challenges and opportunities facing ports and neighboring communities. The key goal from the workshop was to promote engagement with other professionals, experts, and stakeholders to share expertise, ideas and actions that address the many opportunities and challenges faced by our nation’s major transportation infrastructure, intermodal facilities/ports and communities.

3.1 Case-Study Ports

The project considered six different ports that were hit by Hurricane Matthew in 2016, (Port of Miami, FL; Port Everglades, FL; Port of Jacksonville, FL; Port of Savannah, GA; Charleston, SC; Port Canaveral, FL). At these ports, pertinent data were collected during Hurricane Matthew. Hurricane Matthew was unique in the fact that it had a direct impact on all six ports. In other words, all six ports were closed at some point during this weather event. Once the models were built, the data from Hurricane Matthew were used to validate the output of these models. This validated model was then used to assess the regional resiliency of these six ports. Each of these ports are vital to the Southeastern United States’ economy and their resiliency is paramount.
They all individually contribute, although in different ways, to this transportation network. Outlined below are the specifics of each port, along with their contributions to the economy of the Southeastern United States.

### 3.1.1 Port of Miami

“Port of Miami is one of the world’s leading hubs for global commerce. Its gateway location in the center of the Western Hemisphere makes the Port a significant conduit for international trade. Port of Miami stands as the U.S. container port closest to the Panama Canal and is the only major logistics hub south of Virginia capable of handling fully laden post-Panamax vessels, providing shippers fast access to Florida’s booming local consumer base and the entire U.S. market. With seven container ports and nine cruise terminals, Port of Miami plays a major role in the international shipping industry.”

“Latin America and the Caribbean makeup 49% of Port of Miami’s trade region in 2018. With the completion of the Deep Dredge Project, trade with Asia will increase from its current 33% as Port of Miami benefits from a shift in trade from West Coast to East Coast ports. As a staple in the global economy, Port of Miami’s remaining trade region comprises of the Europe, Middle East, India, and Africa. In 2018, the total TEU capacity estimated to 1.1 million twenty-foot equivalent units of containerized cargo (TEUs), a 37% increase from 2014. The total value of the economic impact created by cargo containers moving via Port of Miami is estimated at $35 billion dollars to the State of Florida. This economic impact includes increased value added during the production of export cargo, as well as transportation, warehousing, and retail distribution activities for import cargo. This import and export activity generates state income equaling $10 billion dollars, and state and local taxes at approximately $2 billion dollars annually. Equipped with 13 ship-to-shore cranes including six super Post-Panamax, the largest in the Southeastern U.S. and on dock intermodal freight rail connects the port with the national rail system moving goods throughout Florida and the continental U.S. reaching 70% of America’s market within four days.”

“Known as the “Cruise Capital of the World”, Port of Miami is homeport to an unprecedented 22 Cruise lines and 55 of the industry’s most innovative ships. Port of Miami's cruise terminals -- among the most modern in the world -- have been designed to quickly move passengers from land to sea. Port of Miami contributes approximately $43 billion and more than 334,500 jobs to Florida’s economy.”

“In October 2018, Royal Caribbean International officially opened Cruise Terminal A, the Crown of Miami. The new facility serves as homeport to the world’s largest cruise ship, Royal’s Symphony of the Seas. April 2018, Port of Miami and Norwegian Cruise Line’s celebrated the groundbreaking for the new cruise terminal Terminal B, The Pearl of Miami. The facility will accommodate vessels carrying up to 5,000 cruise passengers. It is scheduled to open February 2020. MSC Cruises’ new facilities are in the works, and an MOU with Disney Cruise Line to expand with two cruise ships and a possible new cruise terminal was approved. Virgin Voyages has also proposed building a new terminal in 2021 for its new cruise ship, the Scarlet Lady

Source: [https://www.miamidade.gov/portmiami](https://www.miamidade.gov/portmiami)

### 3.1.2 Port Everglades

“Known as an “economic powerhouse, Port Everglades is one of the busiest cruise ports in the world. It is a leading container port in Florida and among the most
active cargo ports in the United State and is South Florida’s main seaport for receiving petroleum products including gasoline and jet fuel.”

“With more than 6.6 million tons of containerized cargo in Fiscal Year 2017, Port Everglades is the 10th busiest container port in the nation, according to the Port Import Export Reporting Service (PIERS) published by JOC Group Inc. Port of choice for more than 20 shipping lines, Port Everglades is ideal for moving products such as fruit, vegetables, automobiles and apparel to and from Central America, the Caribbean, South America, Europe and even the Far East. Poised with superior customer service and state-of-the-art equipment, Port Everglades has increased its capacity to handle containerized cargo from 880 thousand TEU’s to approximately 1.1 million.”

“Equipped with 9 cranes capable of handling a full range of cargo, Port Everglades has kept pace with Florida’s construction and population demand by moving various bulk/break bulk material to include: imported and exported cement, lumber, steel rebar, cement, aggregate, tallow, and gypsum, handling 1.5 million units.”

“The 43-acre near-dock Intermodal Container Transfer Facility (ICTF) at Port Everglades is operated by Florida East Coast Railway (FECR). The ICTF's advantageous location adjacent to the Port's docks allows international containers to be quickly transferred between ship and rail, reducing congestion on interstate highways and local roadways and reducing harmful air emissions by diverting an estimated 180,000 trucks from the roads by the year 2029.”

“With annual passenger counts of nearly 4 million, Port Everglades holds the distinction of being among the three busiest cruise ports in the world with 10 cruise lines and one daily ferry operator. The total number of cruise and ferry passengers increased by 1 percent for a total of 3,863,662 passengers in FY2017. Multi-day cruise passenger numbers increased by 2 percent from 3,680,549 in FY2016 to 3,738,252 passengers in FY2017. Daily passenger numbers dropped slightly from 145,866 to 125,410 in FY2017.”

Source:  http://www.porteverglades.net

3.1.3 Port of Jacksonville (JAXPORT): “JAXPORT offers service from dozens of ocean carriers, and over the past few years, JAXPORT has added new direct port calls and more than 100 transshipment port calls worldwide. With 1,600+ reefer plugs on dock, and dedicated cold chain supply chain services throughout the region, the Port of Jacksonville is uniquely positioned to safely handle temperature-controlled freight. It offers multiple berths, skilled labor and three major auto processors to move your cars, trucks, SUVs, motorcycles and recreational boats on time and in dealer-ready condition. JAXPORT is equipped with ten non-containerized berths, with 1 million square feet of on-dock warehousing is advantageous to moving breakbulk cargo like lumber, rolls of paper, wood pulp, steel and other metals. JAXPORT offers bulk shippers more than 40 acres of dedicated dry bulk space and 324,000 barrels of capacity for liquid bulk cargo shipments. Port partners are pioneers in the transportation of LNG in an off-pipeline, efficient fuel supply chain from two tanker berths. With a single passenger terminal, Carnival
Cruise Lines’ 2,056-passenger Carnival Ecstasy offers year-round service from Jacksonville, Florida.”

Source: https://www.jaxport.com

3.1.4 Port Canaveral “Port Canaveral is home to three seasonal and six year-round cruise ships from Carnival Cruise Lines, Disney Cruise Line, Royal Caribbean International, and Norwegian Cruise Line, and will welcome an estimated 104 visits by port-of-call vessels in Fiscal Year 2017. With more than 4.2 million revenue passengers last year, Port Canaveral is ranked as the second-busiest cruise port in the world and serves as a popular homeport and port of call for some of the largest ships afloat, including Royal Caribbean International’s Oasis of the Seas and Norwegian Cruise Line’s Norwegian Epic. In November 2016, both of these majestic vessels joined the Canaveral home-ported fleet.”

Port Canaveral has 12 general cargo berths, along with 1 tanker berth. Two deep-water container and multi-purpose cargo berths make Port Canaveral the most economical and convenient ocean gateway for containerized cargo in Florida. 1,800 feet of berthing spaces is equipped with two ship-to-shore cranes able to handle 40.6 metric tons and move 30-40 containers per hour.

“Roll-on/Roll-off specialized shipping facilities are located at South Cargo Pier 4. This secure paved facility covers 16 acres which includes an onsite 20,000 sq foot processing warehouse. Port Canaveral is ideal for importing and exporting new and used RO/RO cargoes. Adjacent to Orlando, the largest auto rental market in the world and home to several automobile and heavy equipment auctions. AutoPort Canaveral, LLC allows for auto inland distribution to all major Florida markets within 3 hours by truck and to over 80 million people in the Southeast US within 8 hours.”

“With unique local aerospace programs, a diverse manufacturing community and a growing regional population, project cargoes through Port Canaveral include everything from specialized industrial machinery to aerospace components to massive defense-related items. Two shore cranes, in addition to a 40 metric-ton capacity mobile harbor crane are available for project cargo. “

“Nearly four million tons of dry and liquid bulk cargo are handled annually at Port Canaveral, including petroleum, aggregates, cement, salt, sand, and slag. Facilities feature a 2,800 foot aggregate conveyer system with a discharge rate of 2,200 tons per hour. Special storage facilities are available for cement, slag and petroleum.”

“In 2016, the Canaveral Port Authority completed $137 million in capital projects, including $45 million in renovations to 24-year-old Cruise Terminal 5, increasing its capacity from 2,500 to 3,500 passengers. In addition, 21-year-old Cruise Terminal 10 was renovated with a capacity increase from 3,200 to 5,500 passengers. Cruise Terminal 8, the Disney Terminal, also received a $2-million upgrade. In addition, the port invested more than $44 million in widening and deepening the harbor and $15.2 million in cargo terminals and backup areas.”

“With 5.5 million tons of cargo in 2016, Port Canaveral serves as the gateway to Central Florida and is located three hours or less from every major Florida market. Last year Port Canaveral
became the exclusive U.S. stop on Streamline’s Blue Stream, a weekly container service operating from Canaveral Cargo Terminal, the first U.S. venture by Gulftainer. In addition, Delaware-based Autoport, Inc. began handling vehicles from the port’s new auto terminal, and Swiss aerospace company, Ruag Space USA, became the first tenant of the Port Canaveral Logistics Center in Titusville.”

“As part of an overall expansion plan, and with a goal of accommodating larger vessels, Phase 1 of a dredging project was completed in late Fiscal Year 2016, which widened Canaveral’s 3.5-mile channel by 100 feet and expanded the current width to 500 feet overall, and initiated the harbor entrance deepening project.”

Sources: [http://flaports.org/ports/port-canaveral/](http://flaports.org/ports/port-canaveral/)  
[https://www.portcanaveral.com/Cargo/Facilities](https://www.portcanaveral.com/Cargo/Facilities)

### 3.1.5 Port of Savannah

“Port of Savannah is home to the largest single-terminal container facility of its kind in North America, is comprised of two modern, deepwater terminals: Garden City Terminal and Ocean Terminal. Together, these facilities exemplify the Port Authorities exacting standards of efficiency and productivity. Garden City Terminal is the fourth busiest container handling facilities in the United States, encompassing more than 1,200 acres and moving millions of tons of containerized cargo annually.”

“Ocean Terminal, Savannah’s dedicated breakbulk and Roll-on / Roll-off facility, covers 200.4 acres and provides customers with more than 1.4 million square feet of covered, versatile storage.”

“Savannah handles about 40 percent of the containerized poultry and is the second busiest container exporter in the U.S. In FY2018, it handled 4.2 million TEUs (Twenty Foot Equivalent Units) in throughput. FY2018 had the highest volume in the Port of Savannah’s history. The Port of Savannah moved 8.6% of total U.S. containerized loaded cargo volume and more than 19% of the East Coast container trade. The port handled 10% of all U.S. containerized exports in FY2018 (USA Trade Online). The Port This port has 25 cranes, 18 berths, one container terminals without rail access, and one with rail access. Accessible to two major interstates as well, creating a direct four-hour drive to Atlanta, Orlando, and Charlotte that are major market cities.”

Source: [http://gaports.com/port-of-savannah](http://gaports.com/port-of-savannah)

### 3.1.6 Port of Charleston

“Port of Charleston is one of the Southeast United States’ busiest container ports. In terms of the dollar value of international shipments, the Port of Charleston Customs district is the eight largest in the United States. In 2018, the Port of Charleston handled almost 2.3 million TEUs of containerized cargo. In 2017, the port moved about 230k vehicles (imports and exports) and handled about 780k tons of non-container cargo. Also the port has 19 cranes, 9 berths, 3 container terminals without rail access, and 3 with rail access. This port generates about $53 billion dollars of South Carolina economic impact and about 187k jobs.”
“The major commodities handled by the Port of Charleston included consumer goods, agricultural products, vehicles, machinery, metals, chemicals, and clay products. The major exports leaving the Port of Charleston include paper and paperboard, wood pulp, auto parts, logs and lumber, fabrics (including raw cotton), and general miscellaneous cargoes.”

“The Port of Charleston handles a wide range of imports. The dominant imported cargoes entering the Port of Charleston include furniture; auto parts; sheets, blankets, and towels; fabrics; tires and tubes; apparel and footwear; household goods; and yarns. Other imports in the Port of Charleston include machinery parts, logs and lumber, hardware, engines, motors, and parts.”

“Over 20 marine carriers move cargo between the Port of Charleston and over 150 nations around the world. Based on the volume of cargo, the Port of Charleston's major trading partners include North Europe (36%), Northeast Asia (22%), India and Southeast Asia (17%), and South America (11%). Other trading partners include the Mediterranean region, Africa, the Middle East, Central America, and the Caribbean.”

“The Port of Charleston offers some of the deepest water in the South Atlantic region. The Port of Charleston maintains a harbor depth of 13.7 meters (45 feet) and a channel depth of 14.3 meters (47 feet) at mean low tide, and it has a tidal lift of from 1.5 to 1.8 meters (five to six feet) that provides from 46 to 14.6 meters (48 feet) depth for ten hours each day. The entrance channel to the Port of Charleston is from 152 to 305 meters (500 to 1000 feet) wide.”

Sources: http://www.worldportsource.com/ports/commerce/USA_SC_Port_Charleston_248.php

4.0 METHODOLOGY

Broadly, the research methodology consisted of three primary tasks. The first task was to define an objective, quantitative approach for evaluating resiliency that would enable a robust performance metric. The second task was developing, calibrating, and validating the hybrid multimode simulation model of the six ports located in the Southeastern United States. When combined with the resiliency assessment performance metric, the simulation model was used as a predictive port resiliency tool. The final task was the development and programing of the evaluation scenarios. The first scenario was a typical 30-day performance period to establish base line of port operations. The second scenario was a 30-day period encompassing the disruption of Hurricane Matthew and the recovery thereafter.

4.1 Resiliency Definition and Assessment

This research utilizes the National Science Foundation’s (NSF) definition of resilience as “the ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events”. However, while this definition is informative, it lacks a quantitative reference. A quantification of resiliency allows systems to analyze current resiliency, track future improvements, and model possible scenarios. Currently, there are multiple methods of quantifying resiliency, all with their own definition for quantification. A common method used is the scorecard method. The scorecard is a way for stakeholders to assess their resilience using predetermined questions designed to target indicator frameworks. The Department of Homeland
Security has developed the Plan Integration for Resilience Scorecard method to reduce the country’s vulnerabilities to hazards.

A similar method of resiliency quantification is the resilience matrix created by the US Army Corps of Engineers. They utilize a 16-cell decision making matrix based on the Network Centric Warfare doctrine of the military. This matrix produces a quantification of “poor”, “moderate” or “good” resiliency. They also utilize a second method of quantification called the Baseline Resilience Indicator for Communities (BRIC). This method is a composite matrix that calculates a resiliency index value based on up to six sub-indexes. Utilizing a resilience range of “poor”, “moderate”, “good” or “low”, “medium”, “high” is a common output for resilience quantification. Most inputs for this method require stakeholder feedback for a variety of multiple choice questions.

A third method of resiliency quantification utilizes stakeholder feedback to output delays and queues in operations. This technique was created for assessing seaports by Kamal Achuthan (2011) but has the potential for use across all transportation systems. The Methodology for Assessing Resilience for Seaports (MARS) models the wet and dry side of port operations before outputting delay and queue time. Stakeholders must assess the results and determine if the times are satisfactory for their seaport.

NSF’s definition of resiliency calls for a means of measuring the system’s ability to absorb, adapt, and recover. Figure 1 provides insight into how this can be accomplished. Let function $\omega(t)$ represent a direct measure of system output at any time $t$. System $S$ will undergo five distinctive states. Prior to event $E$ ($t < t_E$), the system is operating in stable, pre-event conditions. After event $E$, output decreases as the system absorbs the impact of the disruption. Eventually, the system will stabilize as the effect of the disruption reaches its maximum impact on functionality. While system performance is no longer decreasing, system output is still reduced from the pre-event conditions $\omega(t_A) \equiv \omega(t_{A+1}) < \omega(t_{E-1})$. The system will remain in the disrupted state until a recovery action is taken at $t = t_D$. The system begins to recover as functionality is restored, $\omega(t_{D+1}) > \omega(t_D)$. This recovery continues until the system reaches a stable recovery at $t = t_R$. 

| PRE-EVENT STATE | STABLE RECOVERED STATE |
Figure 1: Time Dependent Resiliency Plot

The system functionality between $t_E$ and $t_A$ can be used as a direct measure of absorption. In particular, the change in time with respect to functionality, i.e. the inverse of the slope, is an intuitive measure of the system’s ability to absorb. This value can also be normalized between zero and one, by the inverse tangent function. Equation 1 represents the system’s ability to absorb the impact of the event. If the absorption state is 1.0, the disruption has no effect on the system. However, a sharp, negative slope indicates poor absorption and results in a value closer to zero.

$$R_A = \frac{2}{\pi} \tan^{-1}[\omega'(t)]^{-1} \quad \text{Equation 1}$$

Similarly, the system’s ability to recover, can also be measured by the inverse of the slope within the recovery state, $t_D < t < t_R$. Equation 2 quantifies the system’s recovery after a recovery action has been taken.

$$R_R = 1 - \frac{[\tan^{-1}[\omega'(t)]^{-1}]}{\pi} \quad \text{Equation 2}$$

The functionality during the disrupted state represents the system’s ability (or lack thereof) to adapt to the adverse conditions and overcome the disruption. While system performance is no longer decreasing, the inability to “bounce back” is measured in the disrupted state. Equation 3 provides a measure, between zero and one, for the system’s ability to quickly adapt to the new conditions, which exist after the disruption.

$$R_D = \frac{t_D-t_A}{t_R-t_E} \quad \text{Equation 3}$$

Resiliency is a measure of the system’s absorption (Equation 1), recovery (Equation 2), and adaptability (Equation 3), and then a quantifiable measure of resiliency is given as Equation 4.

$$R = R_A * R_D * R_R \quad \text{Equation 4}$$

This formulation of resiliency suggests that if the system is unable to absorb or adapt or recover, it is, effectively not resilient, $R = 0$. Furthermore, this approach also allows for the quantification of robustness, which is defined by NSF as “the loss of service that is induced by a disturbance”\(^1\). The fractional area of system functionality between the disruption and recovery is therefore a direct measure of the robustness of the system and provided in Equation 5.

$$\rho = \frac{\int_{t_E}^{t_R} \omega(t) dt}{\omega(t) + (t_R-t_E)} \quad \text{Equation 5}$$

4.2 Hybrid Multimodal Simulation Model Development

This section will focus on the description of the modeling and simulation of the six case studies (Port of Miami, Port Everglades, Port Canaveral, Port of Jacksonville, Port of Savannah, and Port of Charleston). In order to get a detailed view of the port operations from both the landside and the waterside, in emergency conditions, the micro-simulation tool VISSIM was selected. VISSIM provides the opportunity to simulate a 30-day period while being able to visually depict
the port operations. Along with the visual representation, this tool provides a vast array of performance measures that can describe in detail how the ports are affected by emergency events and their level of resilience. These models are developed from a blank slate and the applicable available data were used to calibrate them. Furthermore, this method was used to ensure the models represented real-life conditions. This technique will be explained further in the methodology.

For the simulation of each port, a simulation period of thirty days was selected, in order to have a clear overview of the whole month in which Hurricane Matthew landed. The other simulation parameters such as the number of random seeds and runs, which are both one for every simulation, were determined for a total of thirty simulations. The random seeds and simulation runs have a value of one because each seed has a separate simulation run with the inputs for the waterside arrival times. The performance measures that were used for the evaluation of the model are the vehicle network performance and the data collection using data collection points for each vessel type. The vehicle network performance gives an overview of both the landside and the waterside network, while the data collection points at the entrance and exit of the port are used in order to collect only waterside data. The aforementioned data was then extracted from the model every hour. The results given in the report are based on an hourly evaluation of the network.

![Figure 2: Hybrid Simulation Modeling Methodology](image-url)
4.3 Landside Model Development in VISSIM

The traffic network of each case study was modeled, and emphasis was placed on the traffic network inside the port and the main transportation corridors that connected to its entrances and exits. To provide more reliable and relevant results, only the roads that are directly connected to the container and passenger terminals have been modeled. The number of lanes, port configuration, and signal timing match that of the actual transportation network and were incorporated into every model. These network attributes were based on Bing Maps built into VISSIM, Google Maps, and DOT data.

Furthermore, all the models that have been developed have static routes, which were built according to the state Departments of Transportation (DOT) traffic data and turning movement counts. Using static vehicle routes, we assume that the turning movements and the routes will be the same for every simulation. The car and truck volumes entering the network were extracted from state DOT data available to the public. The inputs were calculated according to the Average Annual Daily Traffic (AADT) for every corridor separately.

The signal control type used in all the models is the Ring Barrier Controller (RBC) emulator, which can simulate actuated control in a VISSIM model. The features that were edited in RBC were the signal timings, the minimum, maximum recalls, sequence, cycle length, and vehicle detector calls. The signal timing data was gathered from similar intersections (same number of lanes, same configuration) that were found on the City of Boca Raton website.

Additional network attributes were added in the model in order to achieve accuracy in the simulation. These attributes include vehicle speeds, which were set on an average speed of 50 km/h for every type of vehicle, reduced speed areas on the left and right turns, and vehicle detectors that coordinate with each signal head on every intersection.

For the waterside models an average speed of 10 knots was used, which accounts for transit speeds as well as a speed reduction during mooring and un-mooring evolutions. In the models pictured below, the dark grey road (links) represent the ship traffic routes in and out of port for each of the four vessel types studied. Also pictured below are the queue of vessels waiting to enter each port during the respective port closures. A “dummy” public transit line was created for each ship type, 4 in total, to block the flow of ships entering the port during the entirety of the closures.

Port of Miami
For the case study of Port of Miami (Figure 4), the main roads that were modeled along with the side roads are Biscayne Boulevard on the west side of the port, Port Boulevard connecting the port with the mainland, MacArthur Causeway inside the port, and Port of Miami Tunnel connecting Watson Island to Dodge Island. The entrances and exits of the port that were included in the model are the ones from Port Boulevard and from Port of Miami Tunnel.
Figure 3: Port of Miami

Port Everglades
The main roads that were modeled for Port Everglades (Figure 5) are A1A on the North side of the port, US1 on the West side of the port, Port Everglades Expressway connecting the port to the Fort Lauderdale-Hollywood International Airport, and Eisenhower Boulevard inside the port. Except the main roads mentioned, all the side roads that connect the main corridors with the terminals are modeled. All the entrances and exits of the port were drawn including the ones on the intersections of A1A and Eisenhower Boulevard, US1 and East State Road 84, and Port Everglades Expressway and McIntosh Road.

Figure 4: Port Everglades
Port Canaveral
The main corridors that are included in the Port Canaveral model (Figure 6) are A1A on the west side of the port, 401, and George King Boulevard inside the port. Additionally, more links were created for all the side roads that connect the terminals to the main corridors. The main entrance of the port from A1A was modeled. Vessels entering and leaving ports were modeled in VISSIM (Figure 6a).

Figure 5: Port Canaveral

Figure 6a: Port Canaveral Closed with Vessels Queueing

Port of Jacksonville
Since the terminals of the Port of Jacksonville (Figure 7) span along the sides of St. Johns River the terminals in this model are connected through the waterside. The main roads that were modeled in the case of Port of Jacksonville are Heckscher Dr. 105 that connects the Blount Island Marine Terminal with the Dames Point Marine Terminal, and E 21st St. that connects the Talleyrand Marine Terminal to the main corridors adjacent to it. All the entrances and exits of
the port, including the main and side roads, were added to the model. Screen view of an example of the simulation vessels queuing outside the port is depicted in Figure 7a.

![Figure 6: Port of Jacksonville](image)

![Figure 7a: Modeled vessels queuing at closed Port of Jacksonville](image)

**Port of Savannah**

West Bay St. and Main St. are the main corridors that extend across the port Savannah, along the Savannah River, and are part of Port of Savannah model. All the side streets that connect the port terminals with the aforementioned roads were drawn as a part of the whole network. Figure 8a depicts detailed view of a modeled sample road junction in the road network.
Port of Charleston

The simulation model of the Port of Charleston (Figure 9) is mainly based on the waterside, due to the configuration of the port. The terminals are located along the Coast of Cooper River, in different locations. The main road that was modeled is the Mark Clark Expressway (I526) that connects Wando Welch Terminal the rest of the terminals. For the terminals of North Charleston, Columbus, Union Pier, and Veterans are connected through the waterside and the vessel routes. Detailed view of a modeled sample road junction is shown in figure 9a.
4.4 Waterside Model Development

This section discusses the port waterside simulation model development of six case study ports: Port of Miami, Port Everglades, Port Canaveral, Port Jacksonville, Port Savanna, and Port Charleston. A waterside simulation was developed for each of these ports and then intergraded with the landside model within VISSIM. Waterside operations were simulation using the Monte Carlo approach. Fundamentally, Monte Carlo simulations work by estimating unknown values from probability distribution functions. Effectively, vessel arrivals and departures are random variables, however, they can be accurately estimated if enough observations are available. Therefore, using the Monte Carlo approach to simulation modeling, it is possible to generate random arrivals and dwell times that statistically match observed port operations. In effect this procedure allows for the generation of a “typical” day, week, or month of vessel traffic that is statistically similar to reality.
The Monte Carlo simulation approach required extensive data collection and processing to identify the underlining statistical distributions which represent the port system. The vessel data were analyzed to identify probability distributions of vessel arrivals and dwell time by cargo type and time of day. From this analysis it was possible to determine, with quantifiable accuracy, the probability of a vessel arrival, its dwell time, and its cargo type. For example, the Monte Carlo simulation estimates the likelihood of a container vessel arriving between 7:00 and 8:00 AM and dwelling for 25 to 26 hours before departing. From this information, the Monte Carlo simulation generates random arrivals and dwell times that correspond to the observed probabilities. Vessel arrivals (if and when a vessel is generated in the network) and dwell times (how long each vessel occupied the berth), was modeled through a process called random inverse sampling. The results of the Monte Carlo simulation were evaluated both for goodness-of-fit qualitatively, by plotting simulated distributions alongside observed and quantitatively using regression analysis.

To develop the Monte Carlo simulation of the six ports, 12 months of AIS data from each port was purchased from MarineTraffic.com to develop the needed arrival and departure distributions. Vessels were categorized into four broad groups: 1) Containerized Cargo, 2) Non-containerized Cargo, 3) Tankers, and 4) Passenger Ships. These categories were chosen for their pervasiveness at each port and the unique loading and unloading characteristics of the cargo they carry. The data contained 71,795 records of vessel arrivals, departures, and dwell time, starting January 1st, 2016 and ending December 31st, 2016. Three additional months of data was also purchased for each port for model validation purposes. This data encompassed January 1st, 2017 through March 31st, 2017.

Table 1 summarizes the number arrivals, by category within the study ports. From the table it can be seen that most of the vessels carried containerized cargo. These four vessel categories make majority of cargo vessel observations within the study ports. For this reason, the simulation models were focused on only these four vessel categories.

<table>
<thead>
<tr>
<th>Table 1: Cargo Type by Study Port</th>
</tr>
</thead>
<tbody>
<tr>
<td>NUMBER OF VESSELS THAT ARRIVED BETWEEN 1/1/2016 &amp; 12/31/2016</td>
</tr>
<tr>
<td>MIAMI</td>
</tr>
<tr>
<td>----</td>
</tr>
<tr>
<td>CONTAINER 980</td>
</tr>
<tr>
<td>NON-CONT. 613</td>
</tr>
<tr>
<td>TANKER -</td>
</tr>
<tr>
<td>PASSENGER 1055</td>
</tr>
</tbody>
</table>

With the data stratified by cargo type, frequency distribution functions were developed for vessel arrivals and vessel dwell time. Vessel arrivals were categorized into one-hour bins, i.e., if a vessel arrived at 4:25 AM, then it was counted in the 4:00 AM – 5:00 AM bin. Vessel dwell times were also categorized into one-hour bins, i.e. if a vessel dwelled for two hours and forty-five minutes, then it was counted in the two three-hour bin. This approach was taken for all cargo types and all hours of the day. The next step was to generate the probability distribution function (PDF) by dividing the frequency distribution by the total number of observed vessels. The cumulative distribution function (CDF) is the integral of the PDF and was generated for vessel
arrival time and dwell time. Figure 9 and

Figure 10 show the arrival and dwell time PDF and CDF for container vessels at Port Everglades, respectively. The figure shows the arrivals to be more or less uniformly distributed. Dwell times for container vessels at the Port Everglades appear to be a right skewed, normal distribution. The arrival CDF appears to be linear, again suggesting a uniform distribution and the dwell time CDF displayed a distinctive “S-curve”, indicative of a normal distribution.

The arrival and dwell time PDFs are located in APPENDIX A and are displayed alongside the simulated values and values obtained from the validation dataset. In general, vessel arrivals were uniformly distributed throughout the day. However, passenger arrivals were normally distributed within a morning peak period. The distribution of vessel dwell times tended to be unique within each cargo type. Tanker and non-containerized cargo vessels appeared to have a uniformly distributed dwell time. Container vessels tended to be right-tailed normal distributions and passenger vessels appear normally distributed with means in the range of nine to 13 hours.
Vessel arrivals and dwell times were then simulated using the Inverse Transform Sampling method. Fundamentally, this approach uses the inverse of the CDF to transform a uniformly distributed random value into an arrival time or dwell time that matches the historic distribution. Using the cumulative distribution function from containerized vessels at the Port of Jacksonville as an example in Figure 11, one-hour vessel arrival bins are shown on the x-axis and the cumulative probability (between zero and one) is shown on the y-axis. Taking the inverse of this function transforms a uniformly distributed random number, through the line shown in the figure and matches it up to a one-hour arrival bin. Effectively, this would be like pointing a finger at a
random value on the y-axis and dragging it toward the CDF line to find the corresponding arrival bin on the x-axis. Figure 12 shows an example of a randomly selected value of 0.7 from a uniform distribution being transformed to a randomly assigned arrival time of approximately 6:00 PM. In this fashion, it was possible to generate random arrivals times that match the observed distributions. Applying the Inverse Transform Sampling Method, vessels arrivals were simulated for 10, one-year periods. This was done to verify or calibrate the vessel arrival model. Once confirmed, a 30-day period was also generated and integrated into the VISSIM simulation of landside operations.

![PORT OF JACKSONVILLE ARRIVAL CUMULATIVE DISTRIBUTION FUNCTION: CONTAINERIZED CARGO VESSELS](image)

**Figure 11: Inverse Transform Sampling Example: Port of Jacksonville Containerized Vessel CDF**

Vessel arrivals were considered a discrete variable falling into any one of 24 time bins. Once a vessel was assigned an hour to arrive, the vessel was projected to enter the port either at the hour, or 15-minutes, 30-minutes, or 45-minutes past the hour. This was assigned on a random basis from a uniform distribution. Vessel dwell times on the other hand are a continues variable and unlike arrivals which only have 24 possible bins, the number of one-hour dwell time bins possible nearly is infinite. Therefore, when developing the dwell time distributions, the number of bins was limited to include most, but not all observed dwell times. Furthermore, because it was desirable for the model to produce a continuous variable for the dwell time, the modeling approach for dwell times was slightly modified. The CDF of the dwell time was approximated to be a linear function. The inverse of this linear approximation was sampled from to generate the dwell times in a similar fashion as the arrival times. This approach to modeling dwell times lead to in less accurate results than other possible methods because of the linearity assumption but was computation efficient. Table 2 shows the linearized inverse sampling questions for vessel dwell times by port and cargo type.
Table 2: Dwell Time Inverse Random Sampling Equations

<table>
<thead>
<tr>
<th>Port</th>
<th>Containerized</th>
<th></th>
<th>Non-Containerized</th>
<th></th>
<th>Tanker</th>
<th></th>
<th>Passenger</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Equation</td>
<td>Min/Max</td>
<td>Equation</td>
<td>Min/Max</td>
<td>Equation</td>
<td>Min/Max</td>
<td>Equation</td>
<td>Min/Max</td>
</tr>
<tr>
<td>Miami</td>
<td>$x - 0.1384$</td>
<td>$0.0175$</td>
<td>$x - 0.1064$</td>
<td>$0.0086$</td>
<td>N/A</td>
<td>N/A</td>
<td>$x + 1.6219$</td>
<td>$0.1602$</td>
</tr>
<tr>
<td></td>
<td>$0.029$</td>
<td>$0.021$</td>
<td>$0.021$</td>
<td>$0.0169$</td>
<td>$0.0335$</td>
<td>$0.1409$</td>
<td>7/15</td>
<td></td>
</tr>
<tr>
<td>Everglades</td>
<td>$x + 0.101$</td>
<td>$0.0409$</td>
<td>$x + 0.0987$</td>
<td>$0.0169$</td>
<td>$x + 0.2714$</td>
<td>$0.0234$</td>
<td>$x + 1.7139$</td>
<td>$0.1808$</td>
</tr>
<tr>
<td></td>
<td>$0.0364$</td>
<td>$0.0155$</td>
<td>$0.0364$</td>
<td>$0.0155$</td>
<td>$0.0236$</td>
<td>$0.0644$</td>
<td>$x + 0.0706$</td>
<td>$0.0644$</td>
</tr>
<tr>
<td>Canaveral</td>
<td>$x + 0.1902$</td>
<td>$0.0327$</td>
<td>$x + 0.0031$</td>
<td>$0.01$</td>
<td>$x + 0.0351$</td>
<td>$0.0173$</td>
<td>$x + 0.1272$</td>
<td>$0.0299$</td>
</tr>
<tr>
<td></td>
<td>$0.0633$</td>
<td>$0.0084$</td>
<td>$0.0633$</td>
<td>$0.0084$</td>
<td>$0.0253$</td>
<td>$0.114$</td>
<td>$x + 1.1455$</td>
<td>$0.114$</td>
</tr>
</tbody>
</table>

4.6 Integrating the Water and Landside Simulation Models

The next step in the development of the simulation models was to incorporate the vessel arrivals which are able to accurately depict the port operations during a major weather event. For this process, a simulated 30-day schedule of port operations was developed for five random seeds or trials for each port. Within VISSIM, vessels were modeled as public transport vehicles to represent sea traffic. Public transport in VISSIM provides attributes that were beneficial in creating the waterside network of the ports. These attributes include departure times, dwell times, routes and stops (berths) for each public transport line.

The procedure that was followed in VISSIM for the waterside model development started by creating the links (paths) for the vessels to travel to and from the port. In order to get more accurate results for each port, only the paths that connect the berths with the entrance/exit of the port were drawn. In each model, the paths were designed according to the geometry of the port and the information of the existing vessel traffic patterns. The link modeling was followed by the establishment of the public transport stops, which represent the port berths. Each public transport stop has the length and the position of the corresponding berth. After the public transport stops, the public transport lines were created. Each public transport line connects to one public transport stop (berth), creating a specific route for every vessel that is destined to that berth. Additionally, each public transport line berth has a specific vehicle type (vessel type). Also, the speeds of all the vessels were varied depending on the traffic patterns and speed restrictions of each specific port.

The simulated vessel arrivals were modeled in VISSIM as public transport departure times. Vessel dwell times were modeled as occupants. The time required for each occupant to exit the public transit vehicle was deterministically set to 999 seconds. The simulate dwell times were
converted to 999 second units and programed as occupants. When the vessel arrives at the berth, it dwells while the “occupants” exits the vessel. Hence, by using public transport lines VISSIM was able to model any type of vessel (container, non-container, tanker, and passenger) to the correct berth at the correct arrival and dwell time.

4.7 Scenario Development

Three simulated scenarios were developed as part of this research. The first scenario represents a typical 30-day period of port operations beginning midnight of September 29th, 2016 and ending at 11:59:59 on October 28th, 2016. This scenario represented the baseline case and was titled as such; Baseline Case. The baseline case scenario established a benchmark for port operations with which to compare subsequent results with. The baseline case scenario results, like all of the modeled scenarios, constitutes five simulated trials or “runs”. When conducting stochastic simulations, runs are needed to rule out the effects of randomness in the model which may impact the research findings. For example, if a fair dice is rolled twice and the result is 2 each time, someone could come to the false conclusion the dice is weighted. However, as the number of runs increase, the likelihood of coming to a false conclusion by chance alone, is reduced.

The second scenario represents the impact of Hurricane Matthew and is titled Hurricane Matthew. Similar to the baseline case scenario, the simulation begins on September 29th, 2016 and has the same five simulation runs as the baseline case (same arrival and dwell pattern). In this scenario, all data for the closure and re-opening of the ports was obtained from the Marine Safety Information Broadcast messages published by the Coast Guard and that data was modeled into each port. Table 3 shows the port closures and reopening times programmed into the simulation. During the closure, access to the port was prohibited. This resulted in a queue of vessels waiting to enter the port. While no such queue existed during Hurricane Matthew (vessel did not wait just outside the port during the storm), it represents a backlog of vessels which would have entered the port, if not for the storm and closure. This scenario also assumed that all vessel in a typical month would call their respective ports and not re-route to do the hurricane. Once each port was reopened in the simulation, the vessel backlog was serviced, resulting in increased demand placed on port infrastructure. Additionally, each vessel was required to wait until berthing space became available. From a modeling perspective, the port was closed by creating a “dummy vessel”. These dummy vessels were set to arrival and occupy the entrance of the port for the duration of the closure. Once the port was reopened, the vessel exited, and port operations resumed. It is noted that in the cases considered here, each port is assumed to be operating at 100% efficiency to service the queue of ships once it is opened. Other situations can be considered as required.

A third scenario was developed to model each port with additional berths for each vessel type after the port opened. The amount of additional available berth space varied between ports and between vessel types. On average additional 2-3 vessels were allowed to be serviced at the same time at a single berth. Allowing additional “hypothetical” berthing space can represent a multitude of real-life scenarios that can greatly help port partners improve their resiliency both on local and regional scales. The most obvious conclusion that can be drawn from this scenario is what infrastructure upgrades can impact the resiliency of a port. Whether it is additional berthing space or, where no more land exists to develop, additional equipment to expedite the onboarding and offboarding of cargo. This scenario can also represent the impact of increasing
the manpower to improve the efficiency of cargo operations. Finally, this scenario involving extended berthing space can also represent ship-to-ship transfer of cargo in order to reduce the queue. For example, it can be used to assess the impact of tanker vessels conducting lightering operations at a tanker barge. These results can assist port partners with pre-storm planning, more specifically potentially pre-staging tanker barges to expedite the clearing of the tanker vessel queue. Multiple results from a scenario of this type can be considered, in support of increasing the resiliency of the ports considered. This scenario is titled Capacity Enhanced in the results in section 5.

Table 3: Port Closures Resulting from Hurricane Matthew

<table>
<thead>
<tr>
<th>PORT</th>
<th>CLOSURE TIME 2016</th>
<th>REOPEN TIME 2016</th>
<th>HOURS CLOSED</th>
<th>ESTIMATED ECONOMIC LOSS (Millions of $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIAMI</td>
<td>10/5 22:00</td>
<td>10/7 10:00</td>
<td>36</td>
<td>169 M</td>
</tr>
<tr>
<td>EVERGLADES</td>
<td>10/5 22:00</td>
<td>10/7 12:00</td>
<td>38</td>
<td>129.2 M</td>
</tr>
<tr>
<td>CANAVERAL</td>
<td>10/5 22:00</td>
<td>10/9 8:00</td>
<td>82</td>
<td>20.5 M</td>
</tr>
<tr>
<td>JACKSONVILLE PASSenger BERTHS</td>
<td>10/6 8:00</td>
<td>10/8 23:00</td>
<td>63</td>
<td></td>
</tr>
<tr>
<td>JACKSONVILLE ALL BERTHS</td>
<td>10/6 8:00</td>
<td>10/9 9:00</td>
<td>73</td>
<td>224 M</td>
</tr>
<tr>
<td>SAVANNAH</td>
<td>10/7 8:00</td>
<td>10/12 7:00</td>
<td>120</td>
<td>600 M</td>
</tr>
<tr>
<td>CHARLESTON</td>
<td>10/7 16:00</td>
<td>10/10 5:00</td>
<td>61</td>
<td>372.1 M</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td>410</td>
<td>1.51 Billion</td>
</tr>
</tbody>
</table>

The last column in Table 3 shows estimated regional economic loss due to the port closures during Hurricane Matthew, based on published data on the contribution each port makes to the local economy and the period of port closure. The estimates do not account for loss revenues for the ships waiting to offload cargo or the cruise ships that had to cancel or change routes. The port closure data was obtained through the Maritime Safety Information Broadcasts published by the United States Coast Guard.

5.0 RESULTS

In this section, the model calibration and validation results are discussed and the results of the vessel activity for the baseline cases and for the studied scenarios are analyzed and compared. The calibration and validation provide a measure of how well the model performed when compared to expectations.

5.1 Model Calibration and Validation

Four separate datasets were used in the calibration and validation of the simulation model. The first was a 12-month dataset acquired to generate the simulation models. This dataset was referred to as 12-Month Cal (calibration) dataset. Next, the simulation model was used to generate ten, 1-year periods. This allowed for the model to generate enough observations to verify the accuracy of simulation predictions. This dataset was titled 10 Year Sim (simulation). Next, five 30-day simulation runs were developed and evaluated for their accuracy. This dataset was titled 30 Day Sim (simulation). Finally, the validation dataset purchased from MarineTraffic.com was also shown to better validate the model findings. The validation dataset was titled 3 Month Val (validation).

The model calibration and validation were conducted in two stages. First, a qualitative assessment was investigated to provide a consensus of how the models performed. This was accomplished by plotting the historical probability distribution functions (12 Month Cal. and 3 Month Val.) alongside the distribution functions generated by the simulation model (10-Year simulation and 30-Day simulation). Figure shows the arrival distribution functions (historic and simulated) for container vessels at the Port of Miami. The figure suggests a general consistency between the four data sources. Appendix A: Arrival and Dwell Time Distribution Functions, contains similar figures for each of the four vessel types at all six case study ports. In general, distribution plots with a higher number of observations and more consistent 12-month historical distributions, showed more consistent model and validation results. Likewise, distribution built upon fewer observations or ones with inconsistent observations made during the 12 historical dataset, produced less stable models results. Overall, the plotted distributions represented the essence of the operations at each port. While dwell times tended to underperform, this was expected because of the linearity assumption made in the modeling process. Furthermore, predicting which hour a vessel would arrive is fundamentally easier than predicting how many hours it is likely to remain within the port.
Figure 13: Port of Miami Containerized Cargo Arrival Time Distributions

The second calibration and validation approach used the coefficient of determination, also known as R-Squared value, to quantitatively evaluate the Goodness-of-fit. Goodness-of-fit refers to how well a simulation model matches the observed values. The coefficient of determination is a measure of how well the model’s regression line estimates the real data points. A coefficient value of one indicates a perfect fit. The coefficient of determination is a strict measure of model performance. Vessels arriving later than expected not only impact the current time period but the following time period as well and necessarily result in an R-Squared value less than 1.0.

For the purpose of this study, the calibration results were estimated by the coefficient of determination when comparing the 12 Month Cal dataset to both the 10 Year simulation and the 30-Day simulation. This was done for vessel arrival time in Table 4 and vessel dwell time in Table 5. The results shown in Table 4 suggest accurate results with regard to when vessel entered the port. R-Squared values ranged between a low of 0.302 and a high of 0.999, with the majority of the results above 0.90. Table 5 shows a range of dwell time R-Squared values between 0.001 and 0.516. This suggest the model struggled to reproduce the exact dwell times seen in the 12 Month Cal dataset. This was expected due to simplified modeling approach taken for dwell times and the assumption of a linear CPF. However, when looking in context of the distribution plots and the strict criteria of the R-Squared measure, the model represented port operations reasonably well for the purpose of the scenario comparisons.
Appendix A, show a general agreement between the model results and the historical datasets. were reflective of the modeling approach, assumpt results. seasonable variability and therefore if any of the ports experience seasonal changes in cargo over a consecutive three-month period. The simulation models developed did not account for seasonal variability and therefore if any of the ports experience seasonal changes in cargo shipments, this would not be reflected in the model. Table 6 shows the validation results for the arrival of vessels. The R-Squared value ranged between 0.001 and 0.729. One reason for the lower R-Squared values could be that the validation dataset was taken over a consecutive three-month period. The simulation models developed did not account for seasonable variability and therefore if any of the ports experience seasonal changes in cargo shipments, this would not be reflected in the model. Table 7 shows the dwell time validation results. The R-Squared value ranged between 0.001 and 0.472. Again, these R-Squared values were reflective of the modeling approach, assumptions, and likely the seasonal impact of port operations. And while these values tend to be lower, the observed distributions, provided in Appendix A, show a general agreement between the model results and the historical datasets.

### Table 4: Arrival Time Calibration Results

<table>
<thead>
<tr>
<th>PORT</th>
<th>CONTAINER</th>
<th>NON-CONTAIN.</th>
<th>TANKER</th>
<th>PASSENGER</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10 YR</td>
<td>30 DAY</td>
<td>10 YR</td>
<td>30 DAY</td>
<td>10 YR</td>
<td>30 DAY</td>
</tr>
<tr>
<td>CHARLESTON</td>
<td>0.998</td>
<td>0.916</td>
<td>0.960</td>
<td>0.358</td>
<td>0.857</td>
<td>0.176</td>
</tr>
<tr>
<td>SAVANNAH</td>
<td>0.997</td>
<td>0.824</td>
<td>0.985</td>
<td>0.754</td>
<td>0.942</td>
<td>0.478</td>
</tr>
<tr>
<td>JACKSONVILLE</td>
<td>0.995</td>
<td>0.821</td>
<td>0.941</td>
<td>0.581</td>
<td>0.951</td>
<td>0.302</td>
</tr>
<tr>
<td>CANAVERAL</td>
<td>0.940</td>
<td>0.376</td>
<td>0.955</td>
<td>0.540</td>
<td>0.929</td>
<td>0.381</td>
</tr>
<tr>
<td>EVERGLADES</td>
<td>0.986</td>
<td>0.485</td>
<td>0.970</td>
<td>0.476</td>
<td>0.974</td>
<td>0.422</td>
</tr>
<tr>
<td>MIAMI</td>
<td>0.998</td>
<td>0.704</td>
<td>0.994</td>
<td>0.706</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

### Table 5: Dwell Time Calibration Results

<table>
<thead>
<tr>
<th>PORT</th>
<th>CONTAINER</th>
<th>NON-CONTAIN.</th>
<th>TANKER</th>
<th>PASS</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10 YR</td>
<td>30 DAY</td>
<td>10 YR</td>
<td>30 DAY</td>
<td>10 YR</td>
<td>30 DAY</td>
</tr>
<tr>
<td>CHARLESTON</td>
<td>0.370</td>
<td>0.473</td>
<td>0.012</td>
<td>0.063</td>
<td>0.150</td>
<td>0.033</td>
</tr>
<tr>
<td>SAVANNAH</td>
<td>0.314</td>
<td>0.350</td>
<td>0.025</td>
<td>0.013</td>
<td>0.003</td>
<td>0.008</td>
</tr>
<tr>
<td>JACKSONVILLE</td>
<td>0.441</td>
<td>0.341</td>
<td>0.308</td>
<td>0.069</td>
<td>0.404</td>
<td>0.132</td>
</tr>
<tr>
<td>CANAVERAL</td>
<td>0.106</td>
<td>0.018</td>
<td>0.017</td>
<td>0.002</td>
<td>0.158</td>
<td>0.154</td>
</tr>
<tr>
<td>EVERGLADES</td>
<td>0.271</td>
<td>0.114</td>
<td>0.170</td>
<td>0.221</td>
<td>0.499</td>
<td>0.310</td>
</tr>
<tr>
<td>MIAMI</td>
<td>0.002</td>
<td>0.001</td>
<td>0.042</td>
<td>0.007</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

For the purpose this research, validation was measured by the R-Squared value generated by the comparison of the simulation datasets and the 3 Month Val dataset. In general, the R-Squared values found during validation are lower when compared to calibration. Table 6 shows the validation results for the arrival of vessels. The R-Squared value ranged between 0.001 and 0.729. One reason for the lower R-Squared values could be that the validation dataset was taken over a consecutive three-month period. The simulation models developed did not account for seasonable variability and therefore if any of the ports experience seasonal changes in cargo shipments, this would not be reflected in the model. Table 7 shows the dwell time validation results. The R-Squared value ranged between 0.001 and 0.472. Again, these R-Squared values were reflective of the modeling approach, assumptions, and likely the seasonal impact of port operations. And while these values tend to be lower, the observed distributions, provided in Appendix A, show a general agreement between the model results and the historical datasets.
Table 6: Arrival Time Validation Results

<table>
<thead>
<tr>
<th>PORT</th>
<th>CONTAINER 10 YR</th>
<th>CONTAINER 30 DAY</th>
<th>NON-CONTAIN. 10 YR</th>
<th>NON-CONTAIN. 30 DAY</th>
<th>TANKER 10 YR</th>
<th>TANKER 30 DAY</th>
<th>PASSENGER 10 YR</th>
<th>PASSENGER 30 DAY</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHARLESTON</td>
<td>0.662</td>
<td>0.630</td>
<td>0.028</td>
<td>0.168</td>
<td>0.007</td>
<td>0.148</td>
<td>0.510</td>
<td>0.394</td>
</tr>
<tr>
<td>SAVANNAH</td>
<td>0.729</td>
<td>0.624</td>
<td>0.041</td>
<td>0.050</td>
<td>0.005</td>
<td>0.004</td>
<td>0.426</td>
<td>0.451</td>
</tr>
<tr>
<td>JACKSONVILLE</td>
<td>0.584</td>
<td>0.413</td>
<td>0.024</td>
<td>0.105</td>
<td>0.095</td>
<td>0.113</td>
<td>0.317</td>
<td>0.405</td>
</tr>
<tr>
<td>CANAVERAL</td>
<td>0.001</td>
<td>0.005</td>
<td>0.072</td>
<td>0.007</td>
<td>0.044</td>
<td>0.037</td>
<td>0.556</td>
<td>0.571</td>
</tr>
<tr>
<td>EVERGLADES</td>
<td>0.355</td>
<td>0.045</td>
<td>0.036</td>
<td>0.021</td>
<td>0.331</td>
<td>0.142</td>
<td>0.639</td>
<td>0.593</td>
</tr>
<tr>
<td>MIAMI</td>
<td>0.021</td>
<td>0.001</td>
<td>0.354</td>
<td>0.372</td>
<td>N/A</td>
<td>N/A</td>
<td>0.421</td>
<td>0.007</td>
</tr>
</tbody>
</table>

Table 7: Dwell Time Validation Results

<table>
<thead>
<tr>
<th>PORT</th>
<th>CONTAINER 10 YR</th>
<th>CONTAINER 30 DAY</th>
<th>NON-CONTAIN. 10 YR</th>
<th>NON-CONTAIN. 30 DAY</th>
<th>TANKER 10 YR</th>
<th>TANKER 30 DAY</th>
<th>PASSENGER 10 YR</th>
<th>PASSENGER 30 DAY</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHARLESTON</td>
<td>0.321</td>
<td>0.387</td>
<td>0.003</td>
<td>0.000</td>
<td>0.028</td>
<td>0.004</td>
<td>0.215</td>
<td>0.184</td>
</tr>
<tr>
<td>SAVANNAH</td>
<td>0.300</td>
<td>0.255</td>
<td>0.001</td>
<td>0.001</td>
<td>0.000</td>
<td>0.001</td>
<td>0.086</td>
<td>0.066</td>
</tr>
<tr>
<td>JACKSONVILLE</td>
<td>0.383</td>
<td>0.325</td>
<td>0.018</td>
<td>0.000</td>
<td>0.073</td>
<td>0.082</td>
<td>0.003</td>
<td>0.001</td>
</tr>
<tr>
<td>CANAVERAL</td>
<td>0.054</td>
<td>0.009</td>
<td>0.001</td>
<td>0.001</td>
<td>0.033</td>
<td>0.010</td>
<td>0.420</td>
<td>0.472</td>
</tr>
<tr>
<td>EVERGLADES</td>
<td>0.173</td>
<td>0.027</td>
<td>0.093</td>
<td>0.041</td>
<td>0.392</td>
<td>0.259</td>
<td>0.240</td>
<td>0.153</td>
</tr>
<tr>
<td>MIAMI</td>
<td>NULL</td>
<td>NULL</td>
<td>0.014</td>
<td>0.003</td>
<td>N/A</td>
<td>N/A</td>
<td>0.034</td>
<td>0.174</td>
</tr>
</tbody>
</table>

5.2 Scenario Results

The simulation results from VISSIM provide a wide range of output parameters. The key measure of effectiveness (MOE) selected to present here was port occupancy. Port occupancy was defined for this research as the number of vessels of a particular cargo type occupying the port at a given moment in time. In this sense, occupancy provides an indication of port capacity. The integration of the waterside and landside models within VISSIM allowed for vessels to interact in both time and space. Therefore, as port becomes congested after the closure, capacity and by extension occupancy become a significant concern for port managers. The port occupancy was determined by analyzing vessel entries and exits.

In general, the most frequent cargo type observed at the case study ports was containerized cargo. This was true for all, but one, port: Port Canaveral. The latter experiences its high traffic from passenger vessels. Because the analysis of port capacity was the primary consideration only the cargo types with the highest demand at each port are described here. A preliminary analysis of the lower demand cargo types found little impact to port operations caused by the storm closures. This was because, in general, these vessels were easily serviced following the port reopening.

Figure shows the containerized cargo vessel occupancy for the Port of Miami. The orange line represents the baseline case scenario, in the absence of the disruption. The blue line shows the modeled port operations during Hurricane Matthew and the black line represents the scenario
involving enhanced port capacity. In general, the impact of the closure on containerized cargo vessels at the Port of Miami was minor. This is to be expected because Miami was located furthest from storm’s path and the port experienced as shorter closure because of this. By integrating the difference between the Hurricane Matthew scenario and the baseline case, an estimate of the total number of lost vessel-hours at Port of Miami was obtained. On average, the simulation model estimated a total of 48 vessel-hours of lost time due to the disruption. Furthermore, it does not appear that capacity enhancements had any meaningful impact on port operations. Again, this was likely because the port was out of the storms direct path and only experienced a minimal disruption.

Figure shows containerized vessel occupancy for Port Everglades. This figure follows the same convention as the prior one. The figure shows a more significant impact on Port Everglades. This was likely because, in general, Port Everglades processes more containerized cargo when compared to the Port of Miami. Port Everglades experienced an estimated 134 vessel-hours of lost time, on average as a result of the closure. However, this was relatively minor as Port Everglades was not directly impacted by the storm and the resulting closure was limited.

Figure shows that the passenger vessel occupancy results for Port Canaveral. It follows the same pattern as the prior two figures. The figure suggests a significantly larger backlog of vessels when the port was reopened. While it is unlikely that passenger vessels would queue in such a way, the analysis does provide for a theoretical examination of the passenger vessel capacity at the port. The total number of vessel-hours lost due to the closure was estimated at around 586. This is nearly eight times the impact felt at Port Everglades. The capacity enhancements provided in scenario three were estimated to reduce the loss by approximately 245 vessel-hours through servicing the queue of vessels more efficiently after the reopening.

Figure shows the containerized cargo vessel occupancy at the Port of Jacksonville. The figure clearly shows a significant impact of the closure on the port as well as extended duration of time needed to address the backlog of cargo vessels. The impact of the closure was felt at this port beginning October 6, 2016 at 1:00 PM and the port did not return to a normal state until October 21, 2016 at 9:00 AM, over two weeks later. The total lost vessel time was estimated at approximately 3,200 vessel-hours. The modeled capacity enhancement case suggested a possible saving of approximately 2,500 vessel-hours as a result of the enhancement.

Figure 18 shows the containerized cargo vessel occupancy at the Port of Savannah. The figure again shows a significant impact of the closure on the port as well as extended duration of time needed to address the backlog of cargo vessels. The impact of the closure was felt at this port beginning October 7, 2016 at 6:00 PM and the did not return to a normal state until the end of the simulation run on October 28, 2016. The total lost vessel time was estimated at over 5,000 vessel-hours. The capacity enhancements showed insignificant change.

Figure 19 shows the containerized cargo vessel occupancy at the Port of Charleston. The figure again shows a relatively significant impact of the closure on the port as well as extended duration of time needed to address the backlog of cargo vessels. The impact of the closure was felt at this port beginning October 7, 2016 at 7:00 PM and did not return to a normal state until the end of
the simulation on October 28, 2019. The total lost vessel time was estimated at over 900 vessel-hours. The capacity enhancements showed insignificant change.

Figure 14: Port of Miami Containerized Cargo Vessel Occupancy Results

Figure 15: Port Everglades Containerized Cargo Vessel Occupancy Results

Figure 16: Port Canaveral Passenger Cargo Vessel Occupancy Results
Figure 17: Port of Jacksonville Containerized Cargo Vessel Occupancy Results

Figure 18: Port of Savannah Containerized Cargo Vessel Occupancy Results

Figure 19: Port of Charleston Containerized Cargo Vessel Occupancy Results
Figure 20 shows the passenger vessel occupancy results for the Port of Savannah. The figure shows the significant impact caused by the closure and ensuing queue of vessel waiting to gain entry into the port. The simulation results suggest the backlog of passenger vessel would likely extend beyond the 30-day simulation period, if actions by port managers were not taken. In reality, many of the passenger vessel trips were canceled or rerouted to other ports. Nevertheless, the simulation provides an excellent example to quantify the benefits gained from the planning and recovery actions taken during Hurricane Matthew. While the Hurricane Matthew scenario did not converge within the simulation time, the total vessel-hours lost at the end of the simulation was approximately 5,000. However, the capacity-enhanced scenario resulted in a total lost time of 1,500 vessel hours, a total saving of 3,500 vessel hours.

![Port of Savannah Passenger Vessels Occupancy](image)

**Figure 20: Port of Savannah Passenger Vessel Occupancy Results**

Figure 21 shows the non-containerized cargo vessel occupancy results from Port Charleston. In general, the port sees only minor non-containerized vessel cargo during the 30-day simulation period. However, the impact of the Hurricane Matthew closure was still felt. The simulation resulted in estimated loss of 240 vessel-hours during the closure and recovery period. The results also suggest that currently capacity levels within the port were sufficient to service the backlog of vessels upon the reopening of the port.

The lost vessel hours at the ports are shown in Table 8 and provide a comparison of the impact of the storm between the ports.
Figure 21: Port of Charleston Non-Containerized Cargo Vessel Occupancy Results

Table 8: Comparative Impact in terms of lost containerized vessel hours

<table>
<thead>
<tr>
<th>Port</th>
<th>Time Closed</th>
<th>Time Open</th>
<th>Hours Closed</th>
<th>Container Vessel Hours Lost Hurricane Matthew</th>
<th>Container Vessel Hours Lost Capacity Enhanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIAMI</td>
<td>10/5 22:00</td>
<td>10/7 10:00</td>
<td>36</td>
<td>48</td>
<td>48</td>
</tr>
<tr>
<td>EVERGLADES</td>
<td>10/5 22:00</td>
<td>10/7 12:00</td>
<td>38</td>
<td>134</td>
<td>134</td>
</tr>
<tr>
<td>CANAVERAL</td>
<td>10/5 22:00</td>
<td>10/9 8:00</td>
<td>82</td>
<td>586(Cruise Ship hours)</td>
<td>341(Cruise Ship hours)</td>
</tr>
<tr>
<td>JACKSONVILLE</td>
<td>10/6 8:00</td>
<td>10/9 9:00</td>
<td>73</td>
<td>3,200</td>
<td>700</td>
</tr>
<tr>
<td>SAVANNAH</td>
<td>10/7 8:00</td>
<td>10/12 7:00</td>
<td>120</td>
<td>5,000</td>
<td>5,000</td>
</tr>
<tr>
<td>CHARLESTON</td>
<td>10/7 16:00</td>
<td>10/10 5:00</td>
<td>61</td>
<td>900</td>
<td>900</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>410</strong></td>
<td><strong>9,868</strong></td>
<td></td>
<td><strong>7,123</strong></td>
<td></td>
</tr>
</tbody>
</table>

5.3 Regional Impact

The impact of Hurricane Matthew to the region was significant. While most of the effects were concentrated in the northern ports, measurable losses were observed at the Ports of Miami and Everglades. The simulated results suggest that in total it is likely that Hurricane Matthew may have caused over 30,000 lost vessel-hours to the region, including a total of over 9,200 containerized cargo vessel hours between the six ports considered. The analysis suggests that without the action taken by the U.S. Coast Guard, U.S. Army Corps of Engineers, and port managers, the adverse effects of this major disruptive event would have been significantly more disastrous. However, the planning and recovery actions pursued in reality mitigated these impacts. The analysis and results suggest an additional opportunity for enhanced regional resiliency. While many of the northern ports experienced significant queues and delays, the southern ports were operating at normal capacity within a few days of reopening. Therefore, for cargo that can be transported over the road network it makes sense to reroute these vessels to
neighboring ports. This would decrease the initial queue or backlog of vessels needing to be 
serviced by the most significantly impacted ports. Decreasing the initial queue would likely have 
an exponential impact on vessel-hours lost because the relationship between initial queue and 
recover time was observed to be non-linear. This was also seen for the modeling of the enhanced 
capacity scenarios. Because at Jacksonville, the port was better able to accommodate the sudden 
surge in vessel traffic, port operations returned to normal sooner and therefore the cascading 
impact of new vessel arrivals did not manifest.
6.0 DISCUSSION AND CONCLUSIONS

A modeling and simulation-based framework has been developed for determining consequences of disruption at ports in a region due to the passage of a hurricane event. In particular, disruptions at a group of case-study ports due to Hurricane Matthew, a category 5 Atlantic hurricane that skirted the southeast US coast in October 2016, are considered. Significant stakeholder engagement through a well-attended workshop, visits to ports and meetings with USCG personnel, and other forums resulted in useful input to the development of the project. The methodology used in developing the framework involves establishment of detailed models of the selected regional ports and their transportation networks on the VISSIM software platform, which together with custom Monte Carlo-based hybrid optimization algorithms integrated into the platforms, as well as libraries of algorithms already built into the platforms, serve as a tool for assessing and planning for the resiliency of regional ports to a hurricane event. The tool analyzes available data on the ports and their normal baseline patterns of operation, including arrivals and departures of intermodal transportation, to predict consequences of a disruptive event. It provides opportunities for exploring the consequences of alternative decisions in responding to a hurricane event. Since each port is unique, the tool is customized with specific models to serve the given port. The general framework for the tool has been established, and a customized tool has been developed for each of the six ports considered: Port of Miami, Port Everglades, Port Canaveral, Port of Jacksonville, Port of Savannah, and Port of Charleston. Baseline operations at the six case-study ports over a 30-day window including the Hurricane-Matthew event were modeled and the impact on normal level of service at these ports due to the disruption caused by the hurricane were evaluated. The results are used to quantify the impact on the ports due to the event and make comparison with available empirical data for the event. It is found that the agreement between the predicted consequences and empirical observations over the event is good where significant input data are available at the individual ports and not so good where limited data are available. The framework can be similarly used to develop a custom tool for any regional port, and similar case studies can be undertaken to answer stakeholder questions relating to the waterside and landside resiliency of a given port.

In general, the results of the research show the benefits of quantifying the impact of an event and how the information gained from such analysis can be beneficial when evaluating alternatives. In the case studies considered, the impact of enhanced service capacities at ports in clearing backlogs was quantified. Such quantitative assessments provide meaning, context, and relevance to port stakeholders that may not be readily apparent at face value. This research also shows that Automatic Identification System (AIS) data could be utilized to create new methods and metrics for the assessment of resiliency in maritime systems. This methodology advances the field of disaster science by expanding on the concepts first proposed by Henry and Ramirez-Marquez (2012) and Baroud et al. (2014) and applying these methods to empirical observations. AIS is an excellent source for quantitative data when seeking post-disaster measures of resiliency. The time dependent performance models developed from this data show the cascading effects of disruptions and quantify the benefits gained by recovery efforts in a time-progressive series. The data show, in quantifiable terms, reductions in performance resulting from the simulated disruption. On a broad level, these findings also represent some of the first steps toward the development of standardized metrics for quantifying MTS operational resiliency. The use of AIS data, which collects information from commercial vessels on a semi-continuous basis, is a rich data source with many applications in disaster science. The methods developed and applied here
quantifies resiliency of regional ports to a hurricane event and can be applied across a range of temporal and spatial scales.

The case studies conducted for the six ports for the disruptive Hurricane-Matthew scenario suggest that the modeling and simulation-based approach considered here is good for predicting the consequences of the related disruptions at the ports and the region, provided sufficient input data about the normal port operations are available. The developed tools allow prediction of possible consequences of making a particular decision from a set of alternative decisions in responding to a disruption and developing an optimal response.

6.1 Plan for Transition

The plan for transition of the developed framework and tools have been discussed with USCG personnel. As described above, the framework for tools specific to a given regional port for determining the consequences of a disruption to the port’s activities due to a hurricane event has been developed. It is based on the establishment of a detailed model of the port and its transportation network on the VISSIM software platform that includes built-in libraries of algorithms for simulating intermodal transportation, and incorporation of custom Monte Carlo-based optimization algorithms onto the platform. Specific tools have been developed for the six selected ports for the case study, in support of assessing and planning for resiliency at these ports. The tools developed can be used to play out various scenarios of interest to USCG and other stakeholders. It has been agreed to house the framework and developed tools within the newly established USDOT supported Freight Mobility Research Institute at FAU that can:

- Provide access and service to stakeholders for predicting consequences of a disruption at any given Port and planning for mitigation of impact of a disruption
- Nurture further development of the framework and associated tools.
- Support other complementary DHS-funded efforts in Port resiliency

The framework and the tools can be improved and further developed, including:

- Refinements to event modeling and simulation to enable consideration of different levels of threats
- Collection of pertinent port disruption data related to recent hurricanes (Matthew, Irma) to support further validation of the developed framework
- Collection of additional port operations data to support improvements to micro-level modeling of intermodal transportation within ports

A manual for running the model is being put together.
7.0 ACKNOWLEDGEMENTS

We are grateful to USCG LCDR Stryker (USCG POC and Project Champion) for providing valuable feedback during periodic conference call meetings and for serving on a panel at the stakeholder workshop in March 2019. The project has benefitted significantly from participation by the following students:

- At FAU: Panagiota Goulianou, LT Maxwell Walker, USCG and LT Joshua Villafane, USCG
- At ERAU: Hannah Thomas, Emily Jannace, and Fanny Kristiansson

The students assisted with running the simulations and with engaging the ports.

We are also grateful to Dr. Hady Salloum and Beth DeFares for supporting the project and for connecting us with project stakeholders.
8.0 REFERENCES


APPENDIX A – ARRIVAL AND DWELL TIME PROBABILITY DISTRIBUTION FUNCTIONS

Containerized Cargo

Figure A1: Port of Charleston Containerized Cargo Arrival Time of Day Distributions

Figure A2: Port of Charleston Containerized Cargo Dwell Time Distributions
PORT OF SAVANNAH ARRIVAL TIME DISTRIBUTIONS:
CONTAINERIZED CARGO VESSELS

PORT OF SAVANNAH DWELL TIME DISTRIBUTIONS:
CONTAINERIZED CARGO VESSELS

Figure A3: Port of Savannah Containerized Cargo Arrival Time of Day Distributions

Figure A4: Port of Savannah Containerized Cargo Dwell Time Distributions
Figure A5: Port of Jacksonville Containerized Cargo Arrival Time of Day Distributions

Figure A6: Port of Jacksonville Containerized Cargo Dwell Time Distributions
Figure A7: Port Canaveral Containerized Cargo Arrival Time of Day Distributions

Figure A8: Port Canaveral Containerized Cargo Dwell Time Distributions
Figure A9: Port Everglades Containerized Cargo Arrival Time of Day Distributions

Figure A10: Port Everglades Containerized Cargo Dwell Time Distributions
Figure A11: Port of Miami Containerized Cargo Arrival Time of Day Distributions

Figure A12: Port of Miami Containerized Cargo Dwell Time Distributions
Non-Containerized Cargo

![Figure A13: Port of Charleston Non-Containerized Cargo Arrival Time of Day Distributions](image1)

![Figure A14: Port of Charleston Non-Containerized Cargo Dwell Time Distributions](image2)
Figure A15: Port of Savannah Non-Containerized Cargo Arrival Time of Day Distributions

Figure 12: Port of Savannah Non-Containerized Cargo Dwell Time Distributions
Figure A17: Port of Jacksonville Non-Containerized Cargo Arrival Time of Day Distributions

Figure A18: Port of Jacksonville Non-Containerized Cargo Dwell Time Distributions
Figure A19: Port Canaveral Non-Containerized Cargo Arrival Time of Day Distributions

Figure A20: Port Canaveral Non-Containerized Cargo Dwell Time Distributions
Figure A21: Port Everglades Non-Containerized Cargo Arrival Time of Day Distributions

Figure A22: Port Everglades Non-Containerized Cargo Dwell Time Distributions
Figure A23: Port of Miami Non-Containerized Cargo Arrival Time of Day Distributions

Figure A24: Port of Miami Non-Containerized Cargo Dwell Time Distributions
Tanker Vessels

Figure A25: Port of Charleston Tanker Vessel Arrival Time of Day Distributions

Figure A26: Port of Charleston Tanker Vessel Dwell Time Distributions
Figure A27: Port of Savannah Tanker Vessel Arrival Time of Day Distributions

Figure A28: Port of Savannah Tanker Vessel Dwell Time Distributions
Figure A29: Port of Jacksonville Tanker Vessel Arrival Time of Day Distributions

Figure A30: Port of Jacksonville Tanker Vessel Dwell Time Distributions
Figure A31: Port Canaveral Tanker Vessel Arrival Time of Day Distributions

Figure A32: Port Canaveral Tanker Vessel Dwell Time Distributions
Figure A33: Port Everglades Tanker Vessel Arrival Time of Day Distributions

Figure A34: Port Everglades Tanker Vessel Dwell Time Distributions
Passenger Vessels

**Figure A35:** Port of Charleston Passenger Vessel Arrival Time of Day Distributions

**Figure A36:** Port of Charleston Passenger Vessel Dwell Time Distributions
Figure A37: Port of Charleston Passenger Vessel Arrival Time of Day Distributions

Figure A38: Port of Savannah Passenger Vessel Dwell Time Distributions
Figure A39: Port of Jacksonville Passenger Vessel Arrival Time of Day Distributions

Figure A40: Port of Jacksonville Passenger Vessel Dwell Time Distributions
Figure A41: Port Canaveral Passenger Vessel Arrival Time of Day Distributions

Figure A42: Port Canaveral Passenger Vessel Dwell Time Distributions
Figure A43: Port Everglades Passenger Vessel Arrival Time of Day Distributions

Figure A44: Port Everglades Passenger Vessel Dwell Time Distributions
Figure A45: Port of Miami Passenger Vessel Arrival Time of Day Distributions

Figure A46: Port of Miami Passenger Vessel Dwell Time Distributions