DEVELOPING A FRAMEWORK FOR ANALYZING THE RESILIENCE OF FORWARD EXPEDITIONARY PORT REFUELING INFRASTRUCTURE

Pulliam, Daniel B.

Monterey, CA; Naval Postgraduate School

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by

Daniel B. Pulliam

March 2021

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The U.S. Navy (USN) relies on ports to enable operations and project power, but many of our ports remain vulnerable to attack and natural disaster. To manage future conflict, the USN must plan for port resilience and develop resilience-enabling technologies that support ship refueling operations. We develop a framework and model capable of studying refueling at ports before and after disruptions. Our framework adapts standard tools for discrete event simulation of ship arrival and refueling, and we demonstrate its use for a simple port. Our methods also enable the analysis of resilience technologies currently being developed by the USN. We study two USN technologies: one enables fast port recovery, and the other enables extended port operations but does not speed up recovery. We find both technologies capable of providing resilience to ports in their own unique ways. Based on our analysis, we provide recommendations for how the USN should deploy both technologies, which enables efficient acquisition and port resilience.

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Lieutenant, United States Navy
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Submitted in partial fulfillment of the requirements for the degree of

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ABSTRACT

The U.S. Navy (USN) relies on ports to enable operations and project power, but many of our ports remain vulnerable to attack and natural disaster. To manage future conflict, the USN must plan for port resilience and develop resilience-enabling technologies that support ship refueling operations. We develop a framework and model capable of studying refueling at ports before and after disruptions. Our framework adapts standard tools for discrete event simulation of ship arrival and refueling, and we demonstrate its use for a simple port. Our methods also enable the analysis of resilience technologies currently being developed by the USN. We study two USN technologies: one enables fast port recovery, and the other enables extended port operations but does not speed up recovery. We find both technologies capable of providing resilience to ports in their own unique ways. Based on our analysis, we provide recommendations for how the USN should deploy both technologies, which enables efficient acquisition and port resilience.
Table of Contents

1 Introduction 1
  1.1 Port Systems .......................................................... 1
  1.2 Ports and Great Power Competition ..................................... 7
  1.3 Port Resilience and Refueling Operations ............................... 10
  1.4 Thesis Goals .......................................................... 12

2 Background and Literature Review 13
  2.1 Port Refueling Operations and Resilience ............................... 13
  2.2 Models of Port Operations and Resilience ............................... 18
  2.3 Our Approach .......................................................... 23

3 Model Development 25
  3.1 Simio Simulation Software ............................................ 25
  3.2 Simio Model of Port Refueling Operations ............................... 27
  3.3 Port Disruptions and Resilience Technologies ............................ 38
  3.4 Port Disruption and Resilience Analysis .................................. 45

4 Results 49
  4.1 Impacts of Disruptions and Resilience Technologies ..................... 49
  4.2 Comparison of Resilience Technologies .................................. 57

5 Conclusion 59
  5.1 Thesis Summary ....................................................... 59
  5.2 Limitations and Areas for Future Work ................................ 61

List of References 63

Initial Distribution List 67
# List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Common Ports and Their Configurations</td>
<td>2</td>
</tr>
<tr>
<td>1.2</td>
<td>Pier and Wharf Examples</td>
<td>5</td>
</tr>
<tr>
<td>1.3</td>
<td>USINDOPACOM Area of Responsibility</td>
<td>9</td>
</tr>
<tr>
<td>1.4</td>
<td>Coverage Areas of Chinese Ballistic and Cruise Missiles</td>
<td>10</td>
</tr>
<tr>
<td>2.1</td>
<td>Potential Threats to Port Operations</td>
<td>16</td>
</tr>
<tr>
<td>2.2</td>
<td>Risk Profile for U.S. Pacific Island Ports</td>
<td>17</td>
</tr>
<tr>
<td>3.1</td>
<td>Baseline Model of Port Refueling Operations</td>
<td>28</td>
</tr>
<tr>
<td>3.2</td>
<td>Simulation Warm-up Period</td>
<td>36</td>
</tr>
<tr>
<td>3.3</td>
<td>Simulation Run Output (Non-Wartime SAG Arrival)</td>
<td>37</td>
</tr>
<tr>
<td>3.4</td>
<td>Simulation Run Output (Wartime SAG Arrival)</td>
<td>37</td>
</tr>
<tr>
<td>3.5</td>
<td>Navy Fuels Infrastructure Rapid Repair Solutions Model</td>
<td>41</td>
</tr>
<tr>
<td>3.6</td>
<td>Seabased Petroleum Distribution System Model</td>
<td>42</td>
</tr>
<tr>
<td>4.1</td>
<td>Disruption Impact (Non-Wartime SAG Arrival Rate)</td>
<td>50</td>
</tr>
<tr>
<td>4.2</td>
<td>Disruption Impact (Wartime SAG Arrival Rate)</td>
<td>50</td>
</tr>
<tr>
<td>4.3</td>
<td>Benefits of NFIRRS (Non-Wartime SAG Arrival Rate)</td>
<td>52</td>
</tr>
<tr>
<td>4.4</td>
<td>Benefits of NFIRRS (Wartime SAG Arrival Rate)</td>
<td>52</td>
</tr>
<tr>
<td>4.5</td>
<td>Benefits of SPDS without Repair (Non-Wartime SAG Arrival)</td>
<td>54</td>
</tr>
<tr>
<td>4.6</td>
<td>Benefits of SPDS without Repair (Wartime SAG Arrival)</td>
<td>54</td>
</tr>
<tr>
<td>4.7</td>
<td>Benefits of SPDS with Repair (Non-Wartime SAG Arrival)</td>
<td>56</td>
</tr>
<tr>
<td>4.8</td>
<td>Benefits of SPDS with Repair (Wartime SAG Arrival)</td>
<td>56</td>
</tr>
</tbody>
</table>
# List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 3.1</td>
<td>Existing and Novel Port Refueling Technologies in the USN</td>
<td>40</td>
</tr>
<tr>
<td>Table 4.1</td>
<td>Percent Demand Met Relative to No Disruption (Non-Wartime)</td>
<td>57</td>
</tr>
<tr>
<td>Table 4.2</td>
<td>Percent Demand Met Relative to No Disruption (Wartime)</td>
<td>58</td>
</tr>
<tr>
<td>Acronym</td>
<td>Abbreviation</td>
<td></td>
</tr>
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<tr>
<td>A2/AD</td>
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<td>BMD</td>
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<td>CI</td>
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<td>CLF</td>
<td>Combat Logistics Force</td>
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<td>CNIC</td>
<td>Commander, Navy Installations Command</td>
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<td>DDG</td>
<td>guided-missile destroyer</td>
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<td>MOP</td>
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<td>SAG</td>
<td>surface action group</td>
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<td>Seabased Petroleum Distribution System</td>
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Executive Summary

The U.S. Navy (USN) relies on ports throughout the Indo-Pacific in order to enable operations and project power throughout the vast region. Many of these remote Pacific Island ports fall within the missile ranges of our adversaries, making them likely targets in an era of renewed great power competition. These facilities are also vulnerable to natural disasters, the effects of climate change, and age-related deterioration of infrastructure components. Destruction or disruption of these critical facilities has the potential to cripple refueling capabilities in the region. As a means to survive, recover, and adapt to these challenges, the USN must plan for port resilience and develop resilience-enabling technologies. In particular, the USN must develop resilience technologies that support refueling operations for wartime and non-wartime ship deployments during and after major port disruptions.

Two organizations in the USN focused on the development of resilience-enabling technologies for Indo-Pacific ports are Naval Facilities Engineering Command (NAVFAC) Engineering & Expeditionary Warfare Center (EXWC) and Naval Sea Systems Command (NAVSEA) Operational Logistics Integration Program (OPLOG). Together, each organization is already developing several resilience-enabling technologies to ensure ship and aircraft refueling during future conflict and disasters. However, there is currently no method for prioritizing the use and deployment of these new technologies. This is problematic as different technologies support resilience in distinct ways. A lack of methods to compare resilience technologies and recommend when and where to deploy them limits their potential benefits and may lead to inefficient acquisition and operational planning.

To address this shortfall, we create a framework to simulate and assess port refueling operations. Our framework centers on discrete event simulation due to the complexity and dynamic nature of port refueling operations, especially after disruptions. We create our framework using objects from Simio’s Standard and Flow libraries that are capable of modeling refueling at any commercial or non-commercial port. We use these pieces to develop a Baseline Model of a simple port consisting of a single channel entrance, single refueling berth, and a single fuel storage tank. We analyze refueling operations with our Baseline Model by simulating military refueling needs during a permissive (non-wartime) and wartime scenario. Together, our framework and Baseline Model offer a simple and...
extensible tool for modeling refueling at real ports in the Indo-Pacific.

One of the benefits of our framework and model is that they enable the analysis of port disruptions on non-wartime and wartime refueling needs. We study the impact that disruptions have on port operations by modeling a disruption that shuts down the berth and tank for 7 days. Results show that even in a non-wartime scenario, a disruption with 7-day recovery time can lead to a 44.2% reduction in total demand met in the 14-days following the disruption. Our model also shows long-term effects lasting 4–6 months after the initial disruption.

Our framework and model also enable the analysis of refueling technologies being developed in the USN to determine their resilience benefits. We study two distinct resilience technologies to show the flexibility of our framework: the Navy Fuel Infrastructure Rapid Repair Solutions (NFIRRS) developed by NAVFAC EXWC and the Seabased Petroleum Distribution System (SPDS) developed by NAVSEA OPLOG. NFIRRS can be understood as a containerized, deployable infrastructure recovery and repair kit, whereas SPDS can be thought of as a submersible fuel barge that acts as a replacement or additional refueling berth. Both technologies enable port resilience, but each provide it in a distinct way. NFIRRS enables fast recovery of failed systems, but does not change system capacity or configuration. In contrast, SPDS enables extended operations beyond that of the original port, but does not speed up recovery of failed systems.

We find both NFIRRS and SPDS capable of providing resilience to ports in their own unique way. In a non-wartime scenario, NFIRRS fast repair nearly eliminates the impact that the disruption has on port refueling operations. However, during a wartime scenario with a surge in arriving USN ships, NFIRRS appears to be less efficient in the near-term (weeks) and long-term (months) after a disruption compared to other resilience technologies. In contrast, SPDS without repair offers an adaptability approach to resilience, resulting in operations being shifted to an entirely new system. We see that this reduces the expected impact of the disruption by approximately 30%, but it leads to a long term drop in performance due to the port having reduced capacity compared its original configuration. Finally, SPDS with repair offers an extensibility approach to resilience, where the port disruption is repaired in conjunction with the deployment of the new system. This configuration not only provides immediate benefit in response to a disruption, but it also leads to better port operations in
the long term. At approximately 6-months post-disruption, we expect SPDS with recovery to provide an additional 5.8% and 10.1% of operational capability during non-wartime and wartime scenarios, respectively.

We recommend that the USN invests in both NFIRRS and SPDS. NFIRRS is easy to deploy and relatively low cost compared to SPDS. NFIRRS is also best suited for non-wartime scenarios out of all the resilience options studied. In contrast, SPDS with repair provides new capacity to extend operations in the long term which leads to better port operations for smaller ports that may need the additional capacity during wartime. On its own, SPDS without repair can help manage and mitigate the impacts of disruptions even when timely port repair efforts are not possible.

Overall, our framework, model, and analysis provides a basis for future work relevant to the USN and Indo-Pacific region. Avenues for future work include implementing and comparing other resilience technologies and exploring the combined effects of multiple resilience technologies. Our methods can also be implemented to study a real-world port or another system configuration (e.g., aircraft refueling).
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There are several people that I would like to thank who have helped me along the way during the writing of this thesis:

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CHAPTER 1: Introduction

Throughout history, ports have played a vital role in commerce, transportation, and survival. Ports and harbors are the backbone waterfront infrastructure linking human activity to the open water. Harbors are coastal areas bounded by natural or artificial structures that provide refuge and protection for maritime vessels during extreme weather events. Ports are areas within a harbor with accompanying facilities for loading and unloading ships, transferring cargo, or moving passengers. In 2014, ports were responsible for over $4.6 trillion in economic activity in the United States, which made up roughly 26% of the nation's economy. In addition to serving a vital economic role by linking land and sea transport and connecting trade partners globally, ports are also critical enablers of power projection, as they extend the operational reach of our forces across the globe.

This thesis focuses on developing models and measures of the resilience of ports and port operations relevant for U.S. Navy (USN) military operations. Historically, the U.S. Department of Defense (DOD) relied on ports owned and operated by the military services for operations and power projection. Shifting threat landscapes, including increased great power competition with near-peer adversaries and natural disasters associated with climate change, requires greater knowledge of how ports operate in contested and disrupted regions.

1.1 Port Systems

The U.S. DOD through the Unified Facilities Criteria (UFC) provides explicit definitions of ports, the systems that comprise ports, and the services they provide for military operations. Department of Defense (2010b, p. 6) defines a harbor as “a water area that is bounded by natural features or manmade structures or a combination of both,” and a harbor is designated as a port when it is “used to transfer cargo or passengers.” When military services use a port, the facility is referred to as a military port—depending on the activity, a military port can also be referred to as a naval base, naval station, naval depot, or naval shipyard (Department of Defense 2010b). Figure 1.1 shows several port configurations.
Ports provide numerous services for ships, including refuge, safe moorings, and protection for vessels during severe weather events and accommodations for water-to-land activities such as refueling, resupply, repair, and the transfer of personnel and cargo. Key port infrastructure that enable these services are piers and wharves and utility systems.
1.1.1 Piers and Wharves

Piers and wharves act as parking infrastructure that enables the safe mooring of ships (Figure 1.2). Department of Defense (2017, p. 164) defines a pier as “a structure that projects out from the shore into the water” onto which ships can be moored. It goes on to describe that piers are usually oriented perpendicular to the shore and are typically used on both sides. Department of Defense (2017, p. 165) defines a wharf as “a structure oriented approximately parallel to the shore” onto which ships can be moored. UFC 4-152-01 classifies piers and wharves into one of four primary types.

Type I - fueling, ammunition, and supply piers and wharves are described as follows (Department of Defense 2017, p. 2):

*Fueling.* These are dedicated piers and wharves equipped with facilities for off-loading fuel from ship to storage and for fueling ships from storage.

*Ammunition.* These are dedicated piers and wharves used for discharging ammunition for storage and for loading ammunition on outgoing ships.

*Supply.* Supply piers and wharves are used primarily for the transfer of cargo between ships and shore facilities. (Department of Defense 2017, p. 2)

Type II - general-purpose piers and wharves are described as follows (Department of Defense 2017, p. 2):

*Berthing.* General-purpose piers and wharves are used primarily for mooring ships. Furthermore, berthing facilities may be active, as when ships are berthed for relatively short times and are ready to put to sea on short notice, and inactive, as when they are berthed for long periods in a reserve status. Depending upon intended pier usage, i.e. active berthing, maintenance/repair, inactive berthing, consider appropriate mooring service type as it relates to design/capacity of mooring fixtures. Activities that typically take place on berthing piers and wharves are personnel transfer, maintenance, crew training, cargo transfer, maintenance, and waste handling. Under some circumstances, fueling and weapons system testing may also be carried out in these facilities. (Department of Defense 2017, p. 2)
**Type III** - repair piers and wharves are described as follows (Department of Defense 2017, p. 2–3):

*Repair.* Repair piers and wharves are constructed and equipped to permit overhaul of ships and portions of a hull above the waterline. These structures are generally equipped with portal cranes or designed to accommodate heavy mobile cranes.

*Floating Dry Docks.* Piers and wharves for floating dry docks are constructed and equipped to permit overhaul of ships above and below the waterline. (Department of Defense 2017, p. 2–3)

**Type IV** - specialized piers and wharves are described as follows (Department of Defense 2017, p. 3):

*Magnetic Treatment and Electromagnetic Roll Piers.* These are piers that moor ships over an array of underwater instruments and large-area cable solenoids used specifically for removing and/or modifying the magnetic signature characteristics of surface vessels and submarines, as well as calibrating the on-board degaussing systems of mine countermeasure vessels.

*Training, Small Craft, and Specialized Vessels.* These piers and wharves are typically light structures designed for specific but limited functions. (Department of Defense 2017, p. 3)
Figure 1.2. Pier and wharf examples. (a) Piers are structures that contain mooring locations oriented approximately perpendicular to the shoreline, whereas wharves are oriented approximately parallel to the shore line, (b) Island wharves are used for the transfer of bulk liquid cargo and are used in areas where the water depths close to shore do not allow for the accommodation of deep draft ships. They consist of a platform on piles connected to shore via submarine pipeline. Source: Department of Defense (2017, p. 7).
1.1.2 Utility Systems
A central function of piers and wharves is to provide ship-to-shore utilities connections (Department of Defense 2017). Some of the main types of utility services that can be found at waterfront infrastructure include (Department of Defense 2010a):

Compressed Air
Compressed air systems are typically required at all repair and active berthing—ships use compressed air for a variety of purposes; while in port, compressed air is mainly used for the operation of pneumatic tools such as grinders, chisels, and painting equipment (Department of Defense 2010a, p. 24).

Electricity
Ships use shore-provided electricity for a number for purposes, these include: hotel service (shore-to-ship power), ship repair (industrial power), systems testing, pier weight-handling equipment, cathodic protection systems, pier lighting, and miscellaneous pier electrical systems (Department of Defense 2010a, p. 74).

Marine Fuel Receiving and Dispensing
Marine fuel receiving and dispensing typically occurs at dedicated fuel piers and wharves that are designed specifically for the handling of fuel; however, “[i]n some cases, permanent fuel piping and system components may be installed on berthing piers which were not primarily designed for handling fuel”—these facilities are typically only used for providing fuel to surface combatants (Department of Defense 2020, p. 95).

Saltwater (Non-potable) Water
Saltwater services are used mainly for flushing/cooling and firefighting; however, the USN requires all vessels at active berth to have self-sufficient saltwater pumping capabilities for such purposes, and shore-provided saltwater systems are typically only provided at facilities used for ship repair at which the vessel does not have self-sufficient saltwater pumping capabilities (Department of Defense 2010a, p. 29).
Steam
Department of Defense (2010a, p. 15) describes that steam systems can be found at most waterfront structures used for ship repair and berthing; however, newer USN vessels do not require steam services, with the exception of nuclear-powered aircraft carriers.

1.2 Ports and Great Power Competition
In the 2017 National Security Strategy (NSS), the U.S. government declared China and Russia to be authoritarian revisionist powers that seek “to shape a world antithetical to U.S. values and interests” (Trump 2017). The NSS further declares that China is attempting to use its rapidly growing political, economic, military power to displace the U.S. as the predominant power in the Indo-Pacific region; meanwhile, “Russia seeks to restore its great power status and establish spheres of influence near its borders” (Trump 2017). To face these challenges, the NSS directs the military to renew America’s competitive advantage and renew its capabilities. The National Defense Strategy (NDS) plays a key role in identifying the capabilities required by the DOD to support the objectives of the NSS.

The 2018 NDS declares that “[t]he central challenge to U.S. prosperity and security is the reemergence of long-term, strategic competition by what the National Security Strategy classifies as revisionist powers” (i.e., China and Russia) (Mattis 2018, p. 2). The document directs the DOD to focus fiscal year 2019–2023 budgets on investments that modernize several key capabilities that directly address the rapid capability advances of U.S. competitors and adversaries. Two of the key modernization areas listed in the NDS that are relevant to our research are (Mattis 2018, p. 6–7):

*Forward force maneuver and posture resilience.* Investments that will prioritize ground, air, sea, and space forces that can deploy, survive, operate, maneuver, and regenerate in all domains while under attack. Transitioning from large, centralized, unhardened infrastructure to smaller, dispersed, resilient, adaptive basing that include active and passive defenses will also be prioritized.

*Resilient and agile logistics.* Investments that will prioritize prepositioned forward stocks and munitions, strategic mobility assets, partner and allied support, as well as non-commercially dependent distributed logistics and maintenance
to ensure logistics sustainment while under persistent multi-domain attack. 
(Mattis 2018, p. 6–7)

In the latest Tri-Service Maritime Strategy that is a collaboration between the USN, the U.S. Marine Corps (USMC), and U.S. Coast Guard (USCG), Berger et al. (2020, p. 5) contends that:

China’s and Russia’s revisionist approaches in the maritime environment threaten U.S. interests, undermine alliances and partnerships, and degrade the free and open international order. Moreover, China’s and Russia’s aggressive naval growth and modernization are eroding U.S. military advantages. Unchecked, these trends will leave the Naval Service unprepared to ensure our advantage at sea and protect national interests within the next decade.

The NSS, NDS, and the Tri-Service Maritime Strategy each place China and Russia as the primary threats to U.S. interests and security throughout world. Together they lay out a strategy to restore the United States’ competitive advantage over China and Russia in order to deter any challenges to the international order that has been in place since the conclusion of World War II. With this aim comes a renewed focus on the Indo-Pacific region.

1.2.1 The Indo-Pacific Region and Ports

The Indo-Pacific region contains over half of the world’s population, the top four economies in the world (U.S., China, Japan, and India), five of the world’s nine nuclear countries (U.S., China, India, North Korea, and Russia), six U.S. treaty ally nations (Australia, Japan, New Zealand, Philippines, Republic of Korea, and Thailand); it also contains the world’s busiest international shipping routes with nine of world’s ten largest seaports (Bowers and Wood 2020). In 2018, U.S. Pacific Command (USPACOM) was renamed U.S. Indo-Pacific Command (USINDOPACOM) in order to signify the importance of the Indian Ocean area as well as Indian Ocean ally nations to the U.S. and its interests (Department of Defense 2018).

Bowers and Wood (2020, p. 2) state, “U.S. installations in the Indo-Pacific stand as littoral bulwarks, situated where all warfighting domains—sea, air, land, space, and cyberspace—intersect and collide. They underwrite the nation’s maritime strength and are the
most tangible expression of U.S. commitments to forward deterrence and defense in the region. Together, they constitute a “shield of the Indo-Pacific,” providing a critical 6,000-mile head start in protecting the U.S. homeland, advancing national interests, and extending the reach, versatility, and endurance of naval expeditionary forces.” These critical installations will be become increasingly tempting targets as the U.S. continues down the path of great power competition with near-peer adversaries.

The Indo-Pacific region is particularly important with respect to great power competition with the People’s Republic of China (PRC). The PRC is rapidly developing, modernizing,
and deploying a sophisticated cruise and ballistic missile arsenal; this arsenal is a key component that enables the implementation of their anti-access/area denial (A2/AD) strategy in the Indo-Pacific region (Center for Strategic and International Studies 2020). Their missile arsenal, partially depicted in Figure 1.4, is comprised of a combination of ballistic and cruise missiles launched from air, land, and sea that are capable of targeting U.S. and U.S. allied military assets in the Indo-Pacific.

Figure 1.4. Coverage Areas of Chinese Ballistic and Cruise Missiles. Figure from Center for Strategic and International Studies (2020)

1.3 Port Resilience and Refueling Operations

The U.S. DOD requires resilient port refueling operations in order to ensure uninterrupted military operations in the Indo-Pacific region. In preparing for a future conflict with a near-peer adversary like China or Russia, the U.S. must be ready to face robust A2/AD strategies combined with increased offensive strike capabilities. Critical port infrastructure
will likely be tempting targets for enemy cruise and ballistic missiles. These facilities are also vulnerable to natural disasters and other events such as age-related deterioration. Destruction or disruption of these critical facilities has the potential to cripple port refueling operations. Infrastructure resilience improvements must be planned for well in advance so that effective resilience investments can be made available when they are needed.

Resilience is defined as “the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions; resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents” (White House Office of the Press Secretary 2013). The term vulnerability, as it relates to critical infrastructure systems, is used “to describe inherent characteristics of a system that create the potential for harm” (Sarewitz et al. 2003). Vulnerability can also be thought of as the degree that a system can be affected by a particular risk (Aven et al. 2018).

1.3.1 Models of Port Vulnerabilities
Assessing resilience first requires measures of system vulnerability. One way we do this is develop a model to capture the logic of the functioning system and use it to measure the impact of specific disruption events or single and/or multiple component failures. This process of identifying the combinations of elements which lead to the loss of the system function will enable the identification of critical vulnerabilities within our port model. From there we will be able to implement and analyze various resilience capabilities in order assess their impact on port refueling operations.

1.3.2 Resilience Capabilities for Port Refueling Operations
Once port vulnerabilities are identified, overcoming these vulnerabilities requires the use of new system designs and operations. The U.S. DOD identified port resilience as a key issue and already leads several efforts to ensure refueling operations in contested and disrupted situations. In particular, two USN organizations that are developing mitigation measures to address some port vulnerabilities are the Naval Facilities Engineering Command (NAVFAC) Engineering and Expeditionary Warfare Center (EXWC) and Naval Sea Systems Command (NAVSEA) Operational Logistics Integration Program (OPLOG). NAVFAC EXWC is the Navy’s primary R&D, test, and evaluation center for shore and near-shore facilities, underwater facilities, and expeditionary equipment (NAVFAC EXWC 2021). They
deliver specialized facilities engineering, technology solutions, and life-cycle management of expeditionary equipment to the Navy, Marine Corps, federal agencies, and other DOD supported commands (NAVFAC EXWC 2021). Their mission is “to identify and apply emerging engineering solutions through engineering, design, construction, consultation, test and evaluation, technology demonstration, implementation, and program management support” (NAVFAC EXWC 2021).

The NAVSEA OPLOG R&D Program focuses on Naval afloat logistics supply chain that supports the Fleet through the Combat Logistics Force (CLF). Their focus is on developing enabling technologies for future and in-service integrated supply systems and for afloat operational logistics. One of OPLOG’s pillars of focus is in Bulk Fuel Distribution. In this pillar, they focus on addressing OPNAV N42 priorities and capability gaps such as: the ability to refuel combatants with current CLF fleet, additional CLF refueling options afloat, refueling combatants in a contested environment, and bulk fuel delivery over the shore.

1.4 Thesis Goals

The goals of this thesis are to develop a discrete event simulation using Simio that models forward port refueling operations that will allow us to assess its capacity to provide combat-logistics support for U.S. naval forces. We will use the model to identify critical vulnerabilities to port refueling operations by modeling operations in a permissive and contested environment. We will establish key measures of performance (MOPs) and measures of effectiveness (MOEs) by which we will be able to compare the port’s performance across the various scenarios. We will then explore various risk mitigation options (infrastructure, repair technologies, active defensive measures, etc.) to assess their impact on the MOPs/MOEs and the overall port resilience. Modeling port operations in both a permissive and a contested environment will provide opportunities to identify ways to increase resilience and improve defensive capabilities.
CHAPTER 2: 
Background and Literature Review

We review the general structure and function of military, commercial, and non-commercial ports to determine key assets and their functions. We then review operational models of port functions that consider port operations at local and regional scales. We relate these models to different approaches to assess port vulnerabilities and the effect of infrastructure disruptions on operations and missions. We build upon these works to develop a framework that supports the modeling and analysis of port operations to support military refueling requirements and missions.

2.1 Port Refueling Operations and Resilience

In general, harbors and ports are comprised of few key infrastructure assets that enable safe ship mooring, off-loading and on-loading of supplies and services, and land-based operations to support these activities. Ship refueling operations at ports relies on a subset of systems meant to enable access and resupply of fuel. We review several of these infrastructures and their current condition as background on key elements that must be considered in a general framework for port operations modeling. We focus attention on ports located in the Pacific region as a key area of military operations for future framework use.

2.1.1 Pacific Island Ports

A detailed assessment of Pacific Island port infrastructure was provided by the Federal Emergency Management Agency (2008) during an evaluation following a magnitude 6.7 earthquake that struck the northwest coast of the island of Hawaii. This assessment was to serve as an evaluation of potential mitigation measures and provide recommendations relevant to other U.S. port facilities on the Pacific Ocean. We use this report to inform the condition of dock structures, fuel tanks, fuel pipelines, and waterfront structures relevant to refueling operations.
Dock Structures
Dock structures (piers, wharves, quays, bulkheads and dolphins) at Pacific Island ports tend to be remnants or expansions of World War II-era infrastructure or even older (1920s), when the use of reinforced concrete was only just becoming a mainstay construction method. The warm and humid environment and high salinity in the air pose significant corrosion problems for structural steel, which in turn causes cracking and spalling that require local repairs. Such repairs as well as earthquake damage repairs tend to make up the bulk of how limited maintenance and repair budgets are spent at remote island ports. It is often difficult to distinguish between pre-existing hidden corrosion damage and damage that is caused by an earthquake. Historically, construction practices at these remote island ports have utilized the locally available coral aggregate; however, more recent construction has employed higher quality aggregate. Sheet piles at these ports consist of both concrete and driven steel. Newer steel sheets typically have cathodic protection, whereas older steel sheets and tieback rods exhibit advanced stages of corrosion, failure, and disrepair.

Fuel Tanks
Federal Emergency Management Agency (2008) concluded that fuel tanks at Pacific Island ports are generally constructed of steel and are designed in accordance with provisions set forth by the American Petroleum Institute; however, they are mostly old and exhibiting kinks or irregular structural deformations that can be attributed to age or use. Tanks older than 50 years of age are not uncommon; however, tank age is generally not a problem with respect to leakage, provided that regular maintenance and painting is performed. Pinhole corrosion can be expected in most tanks of significant age which results in the presence of rainwater on the surface of the fuel oils that are stored within the tank. Similarly, condensation inside of the tanks will lead to internal corrosion. There are no occurrences of catastrophic fuel tank failure at a Pacific Island port in recent history.

Fuel Piping
Fuel piping systems at Pacific Island ports tend to vary in age and in the quality of their construction. Utility designs are typically based on local design practices/techniques, with little attention paid to geotechnical or structural issues. Trench back-fill is mostly granular material; it is usually unknown what, if any, compaction standards were adhered to during
installation. Maintenance and repairs are routinely performed by local maintenance personnel who possess limited experience. The surrounding material of fuel line trenches is generally composed of loose dredged fills that are highly susceptible to seismic movements. The performance of utilities such as underground fuel piping during extreme weather conditions and seismic events is anticipated to be poor. Anticipated failures in such events include severed connections at dock structures and off-site hookups and washout of trench back-fill that could result in severed lines.

**Waterfront Structures**

Waterfront structures at Pacific Island ports tend to consist mostly of transit sheds and operating buildings that are a mixture of reinforced-concrete structures and masonry construction. The age of these facilities is typically consistent with the age of their associated dock structures, so in the case of Pacific Island waterfront structures, this tends to be WWII-era and older. Design standards tend to follow some version of the Uniform Building Code, thus they are reasonably well suited to handle seismic activity and severe weather without collapse (though extensive damage should be expected). Federal Emergency Management Agency (FEMA)’s Seismic Mitigation Guidelines for Pacific Island Ports found little evidence of seismic retrofits or ground improvements at waterfront structures.

**Summary of Pacific Island Port Infrastructure Condition**

The general takeaway from FEMA’s assessment is that Pacific Island port infrastructure is well beyond of its useful economic life, not designed to modern seismic/construction standards, and in need of replacement due to age and corrosion.

**2.1.2 Port Vulnerabilities**

In addition to fuel, key assets and systems are required for port refueling operations. These systems are exposed to a diverse set of span a broad range of factors including: natural disasters, human factors, technological factors, and organizational factors. The fish-bone diagram in Figure 2.1 provides a comprehensive overview of the vulnerabilities facing port operations.
Figure 2.1. Potential Threats to Port Operations. This fish-bone diagram details a comprehensive list of potential threats to port operations that could ultimately result in a port disruption or closure. The potential threats are grouped into seven factor classifications: economic, environmental, human, access, network, technological, and organizational factors. Source: Grainger and Achuthan (2014).

Earthquakes are one of the key natural disaster vulnerabilities facing ports in the Pacific. Figure 2.2 summarizes the risk profile for several key Pacific Island ports to earthquakes. The majority of the remote Pacific Island ports listed are under a significant risk for seismic disruptions that carry severe consequences due to the lifeline role that the ports provide their respective islands.
### Figure 2.2. Risk Profile for U.S. Pacific Island Ports

The conceptual seismic risk profile for Pacific Island ports following a 2008 FEMA assessment. The majority of the remote Pacific Island ports are under significant risk for seismic disruptions that carry severe consequences due to the lifeline role that the ports provide their respective islands. Source: Federal Emergency Management Agency (2008).

<table>
<thead>
<tr>
<th>Location1</th>
<th>Seismic Risk1</th>
<th>Piers</th>
<th>Buildings</th>
<th>Fuel Tanks</th>
<th>Utilities</th>
<th>Site/ Jetties</th>
<th>Consequence of Seismic Failure3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kawaihau, Hawaii</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1 – support from Hilo</td>
</tr>
<tr>
<td>Hilo, Hawaii</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>pending</td>
<td>2</td>
<td>1</td>
<td>1- support from Kawaihau</td>
</tr>
<tr>
<td>Kahalui, Hawaii</td>
<td>3</td>
<td>2</td>
<td>pending</td>
<td>3</td>
<td>pending</td>
<td>2</td>
<td>2 – minor support from Lahaina</td>
</tr>
<tr>
<td>Lanai, Hawaii</td>
<td>3</td>
<td>2</td>
<td>pending</td>
<td>pending</td>
<td>pending</td>
<td>3</td>
<td>2 – support from Maui</td>
</tr>
<tr>
<td>Molokai, Hawaii</td>
<td>2</td>
<td>2</td>
<td>pending</td>
<td>pending</td>
<td>pending</td>
<td>2</td>
<td>2 – support from Oahu</td>
</tr>
<tr>
<td>Lihue, Hawaii</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>pending</td>
<td>2</td>
<td>1</td>
<td>1 – support from Pt Allen &amp; Oahu</td>
</tr>
<tr>
<td>Pago Pago, Samoa</td>
<td>3</td>
<td>3</td>
<td>pending</td>
<td>pending</td>
<td>pending</td>
<td>pending</td>
<td>3 – lifeline to remote islands</td>
</tr>
<tr>
<td>Majuro, Marshall Islands</td>
<td>2</td>
<td>3</td>
<td>pending</td>
<td>pending</td>
<td>pending</td>
<td>pending</td>
<td>3 – lifeline to remote islands</td>
</tr>
<tr>
<td>Port of Guam</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3 – critical strategic hub</td>
</tr>
<tr>
<td>Port of Saipan</td>
<td>3</td>
<td>2</td>
<td>pending</td>
<td>pending</td>
<td>pending</td>
<td>pending</td>
<td>3 – lifeline to remote islands</td>
</tr>
<tr>
<td>Koror, Palau</td>
<td>3</td>
<td>3</td>
<td>pending</td>
<td>pending</td>
<td>pending</td>
<td>pending</td>
<td>3 – lifeline to remote islands</td>
</tr>
</tbody>
</table>

Notes:
1. Seismic risk values are estimated as 1 (low) to 3 (severe).
2. Estimated performance levels range from 1 (best) to 3 (worst).
3. Estimated consequences range from 1 (least impact) to 3 (most impact).
4. Honolulu Harbor, Pearl Harbor, and Apra Harbor were excluded, because they are either large or Department of Defense ports.
2.1.3 Port Resilience

Today’s infrastructure systems have grown to be complex networks of interdependencies. This shift has been aided by the emergence of new technologies and has been driven by the desires of various stakeholders to have systems that operate better, cheaper, faster, and more efficiently. Operating these efficient, interdependent networks has had the unintended consequences of resulting in systems that can be vulnerable to sudden dramatic failure. This has led many to study complex systems with respect to the notion of resilience.

The definition of resilience according to Presidential Policy Directive (PPD) 21 was provided in Section 1.3, and Woods (2015) notes that there are four core concepts of resilience:

- Resilience as **rebound** evaluates how well a system recovers from the disrupting event and returns to its previous activities.
- Resilience as **robustness** can be thought of as the system’s ability to absorb a variety of disturbances. When robustness is increased, the set of potential disruptions that the system can respond to effectively is expanded.
- Resilience as **extensibility** can be thought of as a measure of how well a system with finite resources can be stretched to accommodate events that challenge boundaries.
- Resilience as **adaptability** can be thought of as the system’s ability to change and evolve in response to future surprises.

Overall, a framework for assessing port resilience requires consideration of system function for refueling, model flexibility to consider a diversity of vulnerabilities, and ways to quantify the benefits of rebound, robustness, extensibility, and adaptability.

2.2 Models of Port Operations and Resilience

In general, past studies on port resilience focus attention on modeling system function, vulnerabilities, resilience capacities, or a combination thereof. Few studies are comprehensive to inform all aspects of port resilience. Moreover, much of the previous work concerning port resilience has focused on the role maritime ports play in national or global supply chains, rather than modeling the operations within a single port or system of ports. We review several studies that inform technical methods for measuring port operations and system function, the impact of failures and disruptions on the port, and the benefits of resilience-enabling technologies.
2.2.1 Port Resilience and the Maritime Supply Chain

Wendler-Bosco and Nicholson (2020) provide an extensive literature review on the research into the impact of port disruptions on the maritime supply chain. The authors also examine the existing body of literature on port resilience and note that the number of available studies examining port resilience or disaster resilience is scarce. The authors point out that there is insufficient work to properly understand the cascading effects that port disruptions can have on the entire supply chain. Wendler-Bosco and Nicholson conclude by stressing the importance for filling the research gaps in port resilience given the importance of ports in global supply chain, coupled with their susceptibility to natural disasters and other disruptions.

Wendler-Bosco (2020) provides research that gives insights related to tropical cyclones and their potential impacts to the coastal United States, particularly with respect to disruptions to ports and the maritime supply chain. Wendler-Bosco provides an extensive review on the resilience of the maritime supply chain, and uses machine learning coupled with historical data on hurricanes and tropical storms to explore and quantify the relationship of tropical storm characteristic and their destructive outcomes. The author develops multiple mathematical models to predict the economic impacts of tropical events. Finally, the author extends this work to provide state-level coastal vulnerability analysis to aid decision-makers in improving community resilience.

Becker et al. (2015) examines the impact that climate change is having and will continue to have on human-environmental systems. In particular, the authors look at the impact that increased storm activity and rising sea levels have on seaports, which are especially vulnerable to these conditions due to their high-risk and environmentally sensitive locations. The authors’ study provides a detailed analysis of the impact that hurricanes have on various seaport stakeholders and is intended to benefit planners, practitioners, and other decision-makers who are responsible for the formulation and implementation of seaport policy and resilience plans.

2.2.2 Network Flows

Pidgeon (2008) introduced and developed a simulation modeling tool to evaluate the disruptions, delays, and incremental costs associated with transportation security incidents
inflicted on the container shipping industry on the U.S. West Coast. Various scenarios, such as striking union workers to earthquakes were considered. His operator’s model aids in identifying potential bottlenecks and vulnerable infrastructure components, improving security and capacity on existing commercial transportation infrastructure subject to the constraint of limited available funding.

Bencomo (2009) extends the work of Pidgeon (2008) by developing a multi-modal network flow model to represent the transportation of containerized cargo entering North America from the East Coast and the West Coast. Bencomo’s attacker-defender model can be used as a tool to help understand the potential impact of various disruptions to the maritime shipping industry.

Babick (2009) introduces a method of performing network analysis on critical infrastructure networks using a “Design-Attack-Defend model that determines the optimal defense plan for a critical infrastructure network within a specified budget constraint” (Babick 2009). The author demonstrates that this yields a solution that is at least as good as the Risk Analysis Management for Critical Asset Protection (RAMCAP) that is used by the U.S. Department of Homeland Security (DHS).

Onuska (2012) developed an Operator’s Model that accurately models real system behavior of coal transport through the Port of Pittsburgh. The author’s work allows for the testing of various “what-if” threat scenarios. This work ultimately allows for the relative assessment of critical infrastructure components in order to aid the USCG in better understanding the criticality of the complex port system.

### 2.2.3 Queueing Networks

Ghosh Dastidar and Frazzoli (2011) present a framework for the stochastic scheduling of aircraft carrier flight deck operations using queueing networks. They represent each station that services the aircraft as separate nodes of the queueing network. They use this approach to find an optimum scheduling policy that can be implemented by human decision makers at each node. They demonstrate how their approach can handle system disruptions, like unplanned outages, and show how it can be applied to a variety of other applications.
Schroder (2014) applies a non-finite queueing theory to model the Port of Durban Container Terminal in South Africa. He uses this model to obtain the ideal number of vehicles and equipment necessary to yield a balanced system in which the least congestion and number of delays is achieved. He then uses Simio simulation software to create a simulation model to simulate the container terminal environment of the Port of Durban. The simulation model is used to gain a different perspective by which to compare the results of the queueing theory model to. Both modeling approaches yielded similar results that shared the same basic concepts. His work resulted in recommendations for the number and type of weight handling equipment in order to increase the container throughput at the Port of Durban.

### 2.2.4 Simulation Modeling

Geiser (2012) develops a discrete-event simulation to model airfield refueling operations. Geiser uses this model to examine ways to improve aircraft refueling at Naval Air Station (NAS) Oceana by adjusting key refueling parameters such number of fuel trucks available, fuel level of each truck, and fuel flow rates. The author uses experimental design to analyze and compare different decisions and provides NAS Oceana with recommendations for improving efficiency and reducing fuel wait time.

Diogo et al. (2015) proposes and tests a procedure that couples stochastic queueing theory models and agent-based simulation to allow for flexible port logistics management. The authors consider an intermodal terminal where transport scheduling was performed by an informed decision-maker at remote points in the system. The author then used Simio to implement a simulation model that allows for the evaluation of the various decisions used by the decision-maker and to assess the impact they would have on the rest of the export logistics chain. The authors’ work resulted in useful insight in identifying key elements necessary in order to reduce the impact of route congestion on a port logistic chain.

Shen (2017) presents a hybrid model for simulating the fuel supply, demand, and inventory of remote coastal and island communities in British Columbia. Shen develops a hybrid model consisting of a combination of system dynamics, agent-based, and discrete-event modeling. The author uses this hybrid model to aid in the understanding of fuel resilience by introducing various fuel disruptions and examining the results from the demand-side perspective. Shen applies the model to a real case study location and uses it to test the
effectiveness of various resilience strategies that the community can implement to help better withstand fuel disruptions.

Kotachi (2018) develops, implements, and validates a novel framework for simulation-optimization to study the influence of using ordered decision variables for the optimization of resource allocation problems. Kotachi develops a large-scale discrete-event simulation model of a complex container terminal which is used to implement and validate the framework based on a real system. The author demonstrates the benefit of using discrete event simulation to accurately model a complex stochastic system.

Vogel (2019) develops a discrete-event simulation for analyzing ballistic missile defense (BMD) strike operations using Simio simulation software. The author models various system components in left-of-launch theater ballistic missile (TBM) operations in order to compare various system metrics focused on delaying the launch of TBMs. The author’s work results in a notional model and experimentation method that can aid in determining optimal locations for BMD operations.

### 2.2.5 Quantifying Resilience

Pant et al. (2014) present a mathematical and modeling framework for the analysis and quantification of system resilience. The authors introduce stochastic measures of resilience in order to quantify the resilience of inland waterway ports. The authors’ work is intended as a basis for framework development related to resilience decision making.

Xu et al. (2019) establish a modeling framework that can be used to measure resilience of the handling chain system (HCS) at container ports. The authors use linear and non-linear models to establish measures of resilience for the HCS at container ports. The authors’ work is intended to serve as a starting point for framework development related to resilience decision making that can be used to assist in reducing disruption impacts on the port and shipping supply chain.

Russell (2020) proposes a method of quantifying resilience that is consistent with the National Science Foundation’s definition of resilience, “the ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events”. Russell identifies system states by measuring the system output and assigning a value
between zero and one that represents one of the following states: stable pre-event state, absorption state, disrupted state, recovered state, and stable recovered state (Russell 2020). The author shows that this resilience measure can be applied to any transportation system by applying it to several complex, real-world systems, such as maritime ports, airports, and refueling systems.

Hosseini and Barker (2016) provide a method to quantify resilience using a Bayesian network model that quantifies “resilience as a function of absorptive, adaptive, and restorative capacities” (Hosseini and Barker 2016). The Bayesian network model allows various resilience building strategies to be analyzed. The authors demonstrate the utility of this method in assessing intermodal transportation networks using a real-world example of an inland waterway port.

Hagen et al. (2016) developed a modeling paradigm for assessing the operational resilience of the U.S. Air Force (USAF) in a contested, A2/AD environment. In order to frame their problem, they focused on the regions of Southwest Asia and the Pacific. The result of this effort was the Operational Resilience Analysis Model (ORAM) which evaluates various courses of action and their impact on operational capability.

### 2.3 Our Approach

Building on the literature, we create a framework that allows us to simulate port refueling operations. This framework allows us to model system function, measure the impacts of various port disruptions, and measure the benefits of resilience-enabling technologies. We use discrete event simulation of a queuing system combined with continuous flow elements to represent port operations because it enables us to track how port refueling operations and disruptions unfold over time. This approach allows us to perform a detailed comparative analysis of port refueling operations under different system configurations and measure impacts over different time periods after port disruption. Ultimately, our framework and analysis provides recommendations related to the deployment and development of resilience-enabling technologies within the USN.
This chapter describes the discrete event simulation model that we developed to analyze typical port refueling operations. We present the software tool that is used to create the model, we describe the basic building-blocks that make up the model, and finally we describe how those building-blocks are combined to create a model of a simple port that consists of a single refueling berth that is supplied by a single fuel storage tank.

### 3.1 Simio Simulation Software

We use the Simio simulation software package to build our simulation model. Simio is a modeling tool that allows you to build and execute dynamic models of systems so that you can see how the operation of the system plays out over time. It can be used to model a wide variety of types of systems including manufacturing, defense, supply chain, and transportation systems. Each of these systems are similar in that they have entities (parts, trucks, ships, passengers, etc.) that are moving through the system that is constrained by some resource (machines, roads, ports, vehicles, etc.). Modeling these types of systems is accomplished by modeling the flow of entities through the system as well as the resources that constrain that flow (Pegden 2014).

Simio employs an object-based approach to system modeling and simulation combined with animation in which objects are selected from various libraries and placed graphically within the model. Using this approach, we are able to create models that represent refueling operations at existing ports and test resilience technologies that have yet to be developed.

#### 3.1.1 Simio Model Objects

We implement various objects from Simio’s Standard Library and Flow Library in our port model. In this section, we provide general descriptions and characteristics for each of these key object types.
Entities
Model entities are objects that move through the simulation model. Entities are dynamically created by sources, routed over a network of links and nodes, serviced by servers, and destroyed by sinks. Entities can have a designated speed at which they travel through the model. A special entity type from Simio’s Flow Library, called ContainerEntity, has an associated container that is capable of carrying a volume of fluid; the capacity and initial volume of ContainerEntity objects can be specified.

Sources
Sources are objects that generate entities of a specified type and arrival pattern and insert them into the simulation model. The number of entities generated per arrival can be specified explicitly or chosen randomly from a distribution.

Servers
Servers are objects from Simio’s Standard Library that represent a capacity-constrained process such as a machine or service operation. Entities that enter a server undergo a process that can either be designated as a specific time (or time distribution) or a task sequence. A server’s simultaneous processing capacity can be either limited or infinite. Once a server has completed processing, the entities wait in an output queue until they are routed to the next destination.

Tanks
Tank objects are from Simio’s Flow Library and are used to model a volume capacity-constrained location for holding a volume of fluid for distribution within the model. Tanks are interconnected within the system model via FlowConnector objects or Pipe objects. They are filled via Emptier objects, and they deliver fluid to other containers via Filler objects.

Fillers
Filler objects are a unique type of Server object from Simio’s Flow Library used to model capacity-constrained processing locations that fill container entities with quantities of fluid. Fillers deliver fluid that is drawn from a container object.
**Emptier**
Emptier objects are another unique type of Server object from Simio’s Flow Library used to model capacity-constrained processing locations that empty the flow contents of container entities. Emptiers draw fluid from a container object and deliver it to another container object via FlowConnector objects or Pipe objects.

**Links**
Link objects are fixed objects used to define a pathway between two nodes in a model that can be traveled by an entity.

**Sinks**
Sink objects are from Simio’s Standard Library and are used to destroy entities that have finished processing in the model. Entity statistics are recorded as they exit the model through a sink.

**Transfer Nodes**
Transfer nodes are robust objects that allow for paths to be connected as well as the ability to select a specific destination, path, or transfer device.

### 3.2 Simio Model of Port Refueling Operations
We build upon the standard Simio model objects described above to develop a simulation model for port refueling operations. We develop a *Baseline Model* of a port that consists of a single channel entrance, berth (e.g., pier), fuel tank, and pipeline connecting the tank to the berth (Figure 3.1). Our Baseline Model uses model objects from both Standard and Flow Libraries in Simio with parameters and relationships that reflect the structure and function of a realistic port.
Figure 3.1. Baseline Model of Port Refueling Operations. A basic port consisting of a single refueling berth supplied by a single fuel storage tank is created using objects from Simio’s Standard Library and Flow Library. During simulation, system flow is from left to right. Ship and Tanker entities enter the system via ArrivingShips and ArrivingTankers source objects. Each entity is routed through the ChannelEntrance server prior to entering the port. Upon entering the port, Ships are routed to the BerthFiller to receive fuel from Tank1 and Tankers are routed to the BerthEmptier to deliver fuel to Tank1. Once fuel filling or emptying processes complete, Ship and Tanker entities exit the port via sinks ExitingShips and ExitingTankers, respectively. Only a single ship may be within the berth (grey region) at any time, such that Ships cannot receive fuel while Tankers deliver fuel to Tank1, and vice versa.

3.2.1 Port Model Objects
We provide a detailed description of each component in the port model and their parameters for simulation. Note: Our Baseline Model provides a framework for studying multiple port configurations. To emphasize model flexibility, we only define parameter values for those necessary to capture realistic port operations for refueling military ships. We also indicate model parameters that must be set by the model user prior to analysis.
Port Entities

Our port model has two entity objects: Ships and Tankers. Ships are ContainerEntity objects representing guided-missile destroyers (DDGs) arriving for refueling at the port. Ship containers represent the quantity of fuel on the ship in its fuel tank. The fuel level of each Ship is determined upon its creation at the source. Once Ships are created, they are routed to the port channel entrance represented by a Server object. Once a Ship can enter the port, it will access one of the port’s fueling berths, where its fuel tank is filled from the port’s fuel storage via a Filler object. Ships exit the system via a Ship-specific Sink object.

Ships have several key parameters that dictate their needs for refueling during simulation runs:

- **Capacity**: The maximum volume of fuel that can be stored in each Ship entity’s container. We set this value to be 420,000 gallons to represent the fuel tank size of a DDG.
- **Initial Volume**: The volume of fuel that a Ship has in its container upon arrival to the port. We set the incoming fuel level to be a random sample chosen from the triangular distribution with a minimum of 45% full, mode of 65% full, and maximum of 85% full.
- **Speed**: The physical speed of the Ship. We set this to be 10 nautical miles per hour based on the recommended ship speed assumptions for a narrow channel (Department of Defense 2010b, p. 52).
- **Priority**: The priority value for entities arriving at the port channel entrance. We assign Ship priority as low to ensure that other entities arriving at the port receive priority.

Tankers are ContainerEntity objects representing ships arriving to replenish the port’s fuel storage tanks (e.g., an oil barge). Similar to Ships, Tanker fuel capacity and fuel level are variable and determined upon entity creation. Also like Ships, Tankers are routed to the channel entrance (Server). Then, Tankers are routed to one of the port’s fueling berths where its contents are discharged into the fuel storage tanks via an Emptier object. Tankers leave the system via a Tanker-specific Sink object.

There are several key parameters for Tanker entities that dictate their ability to replenish port tanks during simulation runs:
• **Capacity:** The maximum volume of fuel that can be stored in each Tanker entity. We set this value to be 2,940,000 gallons (70,000 barrels) to represent a small general purpose tanker similar to ones that are typically used to transport refined petroleum products to Indo-Pacific ports.

• **Initial Volume:** The volume of fuel that a tanker has upon arrival to the port. We set this value to be 2,940,000 gallons to represent a full tanker arriving to the port.

• **Speed:** The physical speed of the tanker. We set this to be 10 nautical miles per hour based on the recommended ship speed assumptions for a narrow channel (Department of Defense 2010b, p. 52).

• **Priority:** The priority value for entities of this type. We assign Tankers a higher priority than Ships to ensure that precedence is given to replenishing fuel at the port over Ships receiving fuel from the port.

### Port Sources

Our port model has two sources, *ArrivingShips* and *ArrivingTankers*, related to the generation of *Ship* and *Tanker* entities, respectively. The ArrivingShips source generates all Ships arriving into the port system. We set several key parameters for ArrivingShips that set the Ship entity arrival pattern:

• **Entities per Arrival:** This parameter determines how many Ship entities are generated in a given arrival. Specifically, Ships arrive in groups representing a surface action group (SAG) of DDGs. We set the size of the SAG to be a random sample from a uniform distribution of two to five ships per arrival.

• **Interarrival Time:** This parameter represents the time between each arrival generated by the Source object. We assign this to be a random sample from the exponential distribution to model a Poisson process. We use a Poisson process to model independent SAG arrivals as well as incorporate high variability in order to stress test our system. The mean of the exponential distribution is a parameter that can be set by the user by using the property *ShipArrivalRate*.

ArrivingTankers is the Source object that generates all arriving Tanker entities that resupply the port’s fuel tanks. Tankers have a different arrival pattern than Ships defined by the following parameters:
• **Interarrival Time**: Time between each tanker arrival generated by the Source object. Whereas we assume Ship entities arrive based on a Poisson process, we assume Tanker entities arrive based on a set or planned replenishment pattern. Specifically, we assume the ArrivingTanker interarrival time to be the mean number of days between Tanker arrivals. This is set in the model using the property `TankerArrivalRate`.

• **Entities per Arrival**: We set this value to one to represent a single tanker arriving to the port.

**Port Servers**
The Baseline Port Model only has a single server, `ChannelEntrance`. ChannelEntrance is a server that represents a queue for ships to wait outside the port until a refueling berth is available. This simulates real port operations as most ports have limited space for ship entry and exit. There are several parameters that determine the functioning of the Port ChannelEntrance:

• **Initial Capacity**: The ChannelEntrance is a Server with an initial processing capacity of one.

• **Maximum Queue Size**: We model a maximum of five Ships waiting in the queue to be refueled by setting the output buffer capacity of ChannelEntrance to one, its initial processing capacity to one, and its input buffer capacity to three.

• **Processing Time**: We set the processing time to be zero, as this is not a physical processing location; it is simply a holding location for ships to wait for an available refueling berth.

• **Balking Options**: A ship that arrives when there are already five ships in the queue will balk and decide not to enter the ChannelEntrance. This represents a Ship entity needing to travel to different location to receive fuel. The entity is sent to the Ship Sink so that statistics can still be recorded about the unmet demand.

• **Reneging Options**: A ship will wait at the output buffer for a maximum of six hours before they will abandon waiting in the buffer. This ensures that the system will not jam when the port runs out of fuel and that an arriving tanker can get through the channel to replenish the port.
Port Tanks
Our Baseline Port Model only has a single fuel storage tank, \( Tank_1 \), represented by a tank object. Tanks have several key parameters that dictate their ability to receive and deliver fuel:

- **Tank Capacity:** The total volume capacity of the fuel storage tank. We set this value to be 1,000,000 gallons for our Baseline Port Model.
- **Initial Tank Contents:** We set the tank to be full at the start of the simulation run.
- **Tank Input Flow Rate:** We set the flow rate into the tank to be 7,000 gallons per minute which is the recommended design flow rate between a regular tanker and fuel storage (Department of Defense 2020, p. 16).
- **Tank Output Flow Rate:** We set the flow rate to be 1,400 gallons per minute which is the recommended design flow rate from fuel storage to DDGs (Department of Defense 2020, p. 17).

Port Fillers
Our Baseline Port Model only has a single filler, \( BerthFiller \), that pumps contents from the port’s fuel storage tank into the container (fuel tank) of an arriving ship. We set the following parameters to dictate the filler’s behavior while refueling ships:

- **Flow Rate:** We set the flow rate to be 1,400 gallons per minute which is the recommended design flow rate from fuel storage to DDGs (Department of Defense 2020, p. 17).
- **Stop Early Trigger:** We implement a stop early trigger that causes a refueling ship to exit the system early if the port’s fuel storage tanks become empty.

Port Emptiers
Our Baseline Port Model only has a single emptier, \( BerthEmptier \), that pumps contents from an arriving tanker into the port’s fuel storage tanks. We set the following parameters to dictate the emptier’s behavior while refilling tanks:

- **Flow Rate:** We set the flow rate to be 7,000 gallons per minute which is the recommended design flow rate between a regular tanker and fuel storage (Department of Defense 2020, p. 16).
• **Stop Early Trigger:** We implement a stop early trigger that causes an emptying tanker to exit the system early if the port’s fuel storage tank becomes full.

**Port Links**
Our port model uses the path, *Channel*, to represent the channel on which arriving ships and tankers travel to the refueling berth. Several key parameters dictate the characteristic and functionality of the channel:

- **Logical Length:** We set the physical length of the channel to be 0.5 nautical miles.
- **Traveler Capacity:** The maximum number of traveling entities that are allowed on the Path object simultaneously. We set this value to one to represent a narrow channel on which only one ship can travel at a time.
- **Speed Limit:** The maximum speed at which an entity can travel along the path. We set this to be 10 nautical miles per hour based on the recommended ship speed assumptions for a narrow channel (Department of Defense 2010b, p. 52).

Our Baseline Port Model has two additional paths, *BerthFillerPaths* and *BerthEmptierPath*, used to route incoming ships and tankers to the appropriate object type inside the berth. The following parameter governs this decision behavior:

- **Link Selection Weight:** We assign the selection weights of the links connecting the channel to the BerthFiller and BerthEmptier to be a logical expression based on the traversing entity’s priority. Only entities with a priority equal to two (ships) can travel the to the BerthFiller object, whereas only entities with a priority equal to one (tankers) can travel to the BerthEmptier object.

Our Baseline Port Model uses two FlowConnector objects, *FillerPipe* and *EmptierPipe*, which are used to represent the pipes connecting from the refueling berth to the fuel storage tank.

**Port Sinks**
Our port model uses two sinks, *ExitingShips* and *ExitingTankers*, through which all ships and tankers exit the system, respectively.
3.2.2 Simulation of Port Operations

In this section, we describe the way we use the simulation framework to perform model analysis on our Baseline Model. We describe the factors that remain constant throughout each simulation run which represent the port’s configuration. We describe the independent variables that we adjust over the course of multiple simulation runs in order to understand the port’s performance. We describe primary measures of effectiveness and present sample model output that we will use to analyze port performance.

Model Parameters:

There are a number of factors in our Baseline Model that can be configured. Each of these factors can be either parameters that remain the same for each simulation run, or variables that we adjust between simulation runs. The following factors we choose to keep constant as parameters for each Simio experiment:

- **Tanker Interarrival Time:** We assume that Tanker entities have a set arrival time schedule of 7 days for all simulation runs.
- **Number / Capacity of Fuel Storage Tanks:** There is a single fuel storage tank with a total capacity of 1,000,000 gallons.
- **Number of Berths:** There is a single berth that is capable of both delivering fuel to a ship and receiving fuel from a tanker. The berth has the capacity to serve one vessel at a time.
- **Piping and Pumping System Configuration:** There is a single main fuel pipeline connecting the fuel storage tanks to the berth. There is sufficient fuel pumping capacity to provide the design flow rates from Department of Defense (2020, p. 17) of 1,400 gallons per minute from the fuel storage tank to a ship at the berth and 7,000 gallons per minute from a tanker at the berth to the fuel storage tank.
- **Number / Length of Channels:** There is a single channel with a length of 0.5 nautical miles connecting the channel entrance to the port’s single berthing location. The channel supports one vessel travelling in each direction at a time at any given time.

Measures of Performance:

The primary measure of performance (MOP) that we use to understand the run and assess the port’s performance is the percentage of the incoming demand that the port fulfills. To
estimate this value, we measure the percentage of incoming fuel demand that the port is able to fulfill over the course of the entire simulation run:

\[
\% \text{ Demand Met} = \frac{\sum \text{FDS}_{\text{Entering}} - \sum \text{FDS}_{\text{Exiting}}}{\sum \text{FDS}_{\text{Entering}}} \times 100
\]  

(3.1)

where \( \text{FDS}_{\text{Entering}} \) is the fuel demand for Ship entities entering the Baseline Model system from the ArrivingShips Source and \( \text{FDS}_{\text{Exiting}} \) is the fuel demand for Ship entities exiting the Baseline Model system at the ExitingShips Sink. The sum for both parameters in Equation 3.1 is taken for all entities entering and exiting during a user-defined time period. Equation 3.1 results in a scaled values from 0 to 100 representing no demand met to all demand met over the user-defined time period, respectively.

**Simulation Variables:**
To test the ability of the Baseline Port Model to serve different operational environments, we adjust the SAG Interarrival Time to create two main scenarios that we use to test each series of experiments. We call those scenarios “Non-Wartime” and “Wartime”, which we define by setting the \textit{Interarrival Time} parameter for the \textit{ArrivingShips Source} as follows:

- **Non-Wartime Arrival:** This arrival rate relates to normal port operations. We assume the mean interarrival time for this scenario is six days.
- **Wartime Arrival:** This arrival rate relates to situations during wartime when more SAGs will be arriving at the port. We assume the mean interarrival time for this scenario is three days.

**Example Simulation Run with Baseline Model:**
Given the above system configuration, parameter settings, and measures of performance, we simulate port operations with the Baseline Model in Figure 3.1. Each simulation run consists of two periods: the warm-up period and the performance period.

We set a warm-up period of 540 days (approximately 18 months) to reduce startup bias. Simulation models that implement queuing networks tend to have an initial-transient period before the system reaches steady state, and allowing the model to have a warm-up period,
during which no statistics are recorded, is a way to reduce startup bias caused by the initial-transient period (Kelton et al. 2017, p. 95). We determined the length of the warm-up period using a dynamic status plot in our simulation model, Figure 3.2, and observing the point at which the output appeared to reach steady-state.

Figure 3.2. Simulation Warm-up Period. A warm-up period of 540 days is used in order to allow the simulation model to reach steady-state before recording any statistics, thereby reducing the impact of startup bias caused by the initial transient period.

Once the warm-up period is completed, we simulate port operations 10 times to view the variability in how well the Baseline Model serves different demand non-wartime and wartime demand patterns. For each simulation, we measure the system performance using Equation 3.1. We measure this MOP for different time periods representing different moving averages after the warm-up period. Representative results of this analysis process can be seen in Figures 3.3 and 3.4.

Figure 3.3 presents the non-wartime fuel delivery performance of the port in terms of average percent demand met. We can see that in the non-wartime conditions the port reaches steady-state behavior by 60 days and is capable of meeting approximately 89% of the demand. In Figure 3.4, we see that this figure drops to approximately 79% by 180 days in a wartime situation.
Figure 3.3. Simulation Run Output (Non-Wartime SAG Arrival). Percentage of incoming fuel demand that the port is capable of meeting in a non-wartime scenario. Steady-state performance in terms of percent demand met is approximately 89% after 180 days. **Note:** The boxes encompass the 1\textsuperscript{st} and 3\textsuperscript{rd} quartiles with a line drawn at the median separating them—the mean value is represented by an “×”.

Figure 3.4. Simulation Run Output (Wartime SAG Arrival). Percentage of incoming fuel demand that the port is capable of meeting in a wartime scenario. The system does not appear to reach steady-state by 180 days where the percent demand met is approximately 79%.
3.3 Port Disruptions and Resilience Technologies

We build upon our Baseline Model to measure the benefits of resilience technologies being developed by the USN. Before we are able to measure the benefits of resilience, we must first introduce a way of representing disruptions in our port model.

3.3.1 Port Disruptions

Port disruptions are broad and can impact any part of the port system. Some specific examples of port disruptions include:

- **Blocked Channel**: A blocked channel prevents entry into and exit from the port. This can be caused due to improper port maintenance (e.g., dredging) preventing larger ships from entering the port or due to ship failure in the channel blocking other ships from entering and exiting.
- **Disabled Berths**: A disabled berth means that ships entering the port will be unable to safely moor and connect to refueling equipment.
- **Pipe Breaks**: A pipe break prevents the flow of fuel from the fuel tank to the berth. In this situation, ships are able to moor and fuel is available, but the fuel is unable to reach the ship.
- **Disabled Tank**: A disabled tank means fuel stored at the port may be inaccessible. This can be caused by broad issues like leaks and fires. In situations like leaks, tanks need to be patched, and fuel in the tanks can be immediately used. In situations like fires, once the fire is put out, the remaining fuel will need to be filtered prior to use.

While each of these port disruptions have different impacts on port and fuel access, in general, they all cause the same impact on refueling operations in our model — Ships will be unable to refuel and Tankers will be unable to replenish tanks. For representing these effects, Simio has built-in functionality to represent disruptions by using Boolean properties for model objects.

3.3.2 Resilience Technologies

Prior to this thesis, we held stakeholder meetings to determine a set of resilience technologies being developed in the USN. Table 3.1 presents a short list of five new and emerging port resilience technologies identified by stakeholders. In this thesis, we study a subset
of these technologies to identify their resilience benefits for the Baseline Model of ports. Specifically, we assess the Navy Fuels Infrastructure Rapid Repair Solutions (NFIRRS) developed by NAVFAC EXWC and the Seabased Petroleum Distribution System (SPDS) under development by NAVSEA OPLOG.

While modeling the impacts of disruptions is straightforward using our Baseline Port Model, to consider the benefits of resilience technologies we must develop new model objects and add them to our Baseline Model. For this reason, each technology (NFIRRS and SPDS) has its own unique implementation that is an extension of our Baseline Model.

**Navy Fuels Infrastructure Rapid Repair Solutions (NFIRRS) Model**

As described in Table 3.1, NFIRRS can be understood as a containerized, deployable fuel farm infrastructure recovery and repair kit that includes all necessary equipment that enable the recovery of damaged fuel infrastructure. These tools and supplies are critical for fuel infrastructure repair and are not likely to be readily available at a remote Indo-Pacific port. Based on our discussions with NAVFAC EXWC, our assumption for a standard repair time with and without NFIRRS is 1-day and 7-days, respectively.

To implement NFIRRS in our model, we use Simio’s add-on process control logic. An add-on process is a method built into Simio to implement additional behavior that triggers after an event occurs. Add-on processes are in addition to the standard logic of port objects defined above.

Our implementation of NFIRRS uses the add-on process shown in Figure 3.5, when there is a disruption (e.g., a broken pipe), the refueling berth is closed until the disruption is repaired. If NFIRRS is available, the add-on process implements the rapid 1-day repair time before reopening the berth. If NFIRRS is not available, the add-on process implements the standard 7-day repair time before reopening the berth.
<table>
<thead>
<tr>
<th>Mitigation / Technology</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Navy Fuels Infrastructure Rapid Repair Solutions (NFIRRS)</td>
<td>Containerized, deployable fuel farm infrastructure recovery and repair kit. Includes pipe cutters and diverters, valves, pump/filters, flexible hose, clamps, joints, etc. to enable the recovery of damaged fuel farm infrastructure.</td>
</tr>
<tr>
<td>Seabased Petroleum Distribution System (SPDS)</td>
<td>Submersible barge with pumps, hoses, and power conduit from beachhead to barge 1–2 miles off-shore. Can be used as an alternative fueling pier in conjunction with a single anchor leg mooring buoy. Designed to be fully operational within 48 hours.</td>
</tr>
<tr>
<td>Offshore Support Vessels</td>
<td>Commercial off-the-shelf vessels that have the capability to store, transport, and distribute operationally relevant quantities of fuel in the near shore.</td>
</tr>
<tr>
<td>Resilient Expeditionary Agile Littoral Logistics Joint Capability Technology Demonstration</td>
<td>A suite of capabilities to enable commercial barges to operate as offshore logistics hubs in support of expeditionary advanced base operations. Enables the capability to provide ship-to-ship refueling, fuel-over-the-shore, and vertical take-off and landing capability to refuel and re-supply helicopters on deck.</td>
</tr>
<tr>
<td>Underground / Hardened Storage Tanks</td>
<td>Provides protection against missile strike and other forms of kinetic attack.</td>
</tr>
<tr>
<td>Multi-functional Berths</td>
<td>Multiple locations (berths) from which a fuel tanker can replenish the fuel farm.</td>
</tr>
</tbody>
</table>
Our NFIRRS Model is implemented using Simio’s add-on process control logic. When there is a disruption (e.g., a broken pipe), the refueling berth is closed until the disruption is repaired. If NFIRRS is available, the add-on process implements the rapid 1-day repair time before reopening the berth. If NFIRRS is not available, the add-on process implements the standard 7-day repair time before reopening the berth.

**Seabased Petroleum Distribution System (SPDS) Model**

As described in Table 3.1, SPDS can be thought of as a submersible fuel barge that acts as a replacement or additional berth that can be deployed inside and outside of ports. Using our framework for port modeling, SPDS is a specialized model object consisting of a Tank, Filler, Emptier, and Links representing SPDS specifications, access, and connectivity to the original port system. The inclusion of these additional model objects into our Baseline Model generates an SPDS model shown in Figure 3.6. Here, the Baseline Model is extended to include an SPDS Tank, Filler, and Emptier shown in the upper portion of the figure. The SPDS model objects act as an additional, independent berth from the original berth in our Baseline Model. Thus, additional SPDS Link objects are included in the SPDS Model to route and control Ship and Tanker flows to and from each berth.

*Note:* SPDS can be configured to connect into a port and re-route fuel flows via additional pipelines shown in black on the right-hand portion of Figure 3.6. We show these additional pipelines to demonstrate the full functionality of SPDS, but this SPDS configuration requires additional time and is more difficult to implement after a port disruption. For this reason, we do not include these additional pipelines and re-routing of fuel in our analysis.
Figure 3.6. Seabased Petroleum Distribution System Model. Our SPDS Model is an extension of our Baseline Port Model (see Figure 3.1) using Port Model objects. Additional model objects in this model include the SPDS Tank, Filler, and Emptier added above our the Baseline Model berth. These model objects connect into the original port via SPDS Links to the left of these objects that dictate Ship and Tanker entity flows to the SPDS. Additional pipelines can also be added to allow the SPDS to connect into the Baseline Model fuel tank and system. Although they are shown here on the right hand side (black lines), we do not include the effects of these additional pipelines in our analysis.
We provide detailed description of each component in this port model that differs from the port model introduced in the previous section. Unless otherwise noted below, the components in this model function the same as the Baseline Port Model in Figure 3.1.

**SPDS Tank**
Our SPDS Model includes an additional tank, *SPDS Tank*, which represents the fuel storage tank of the SPDS system. Several key parameters dictate the implementation and functionality of SPDS:

- *Tank Capacity*: The total volume capacity of the SPDS fuel storage tank. We set this value to be 600,000 gallons for our Baseline Port Model.
- *Initial Tank Contents*: We set the tank to be full at the start of the simulation run.
- *Tank Input Flow Rate*: We set this to be 1,000 gallons per minute which is the recommended design flow rate to SPDS.
- *Tank Output Flow Rate*: We set this to be 1,000 gallons per minute which is the recommended design flow rate from SPDS.

**SPDS Filler**
Our SPDS Model includes an additional filler, *SPDS Filler*, which represents the location that an arriving ship entity will travel to in order to receive fuel from the SPDS tank. We set the following parameters to dictate the filler’s behavior while refueling ships:

- *Flow Rate*: We set the flow rate to be 1,000 gallons per minute which is the design flow rate for SPDS.
- *Stop Early Trigger*: We implement a stop early trigger that causes a refueling ship to depart the SPDS system once its tank is filled.

**SPDS Emptier**
Our SPDS Model includes an additional emptier, *SPDS Emptier*, which represents the location that an arriving tanker entity will travel to in order to deliver fuel to the SPDS tank. We set the following parameters to dictate the emptier’s behavior while refilling the SPDS tank:
• **Flow Rate:** We set the flow rate to be 1,000 gallons per minute which is the design flow rate for SPDS.

• **Stop Early Triggers:** We implement a stop early trigger that causes an emptying tanker to depart the SPDS system once its tank becomes full.

**SPDS Links**

Our SPDS Model includes several path objects connecting the output of ChannelEntrance to each filler and emptier object at the port’s berth and SPDS system. The way we implement these path objects that represent the channel is one of the primary differences between the SPDS Model and the Baseline Model. Each of these paths represent the same physical location, and the path in the model that a particular ship or tanker will take is decided by selection weights that are governed by carefully developed logical expressions. Those expressions for each path are described below:

• **ChannelEntrance to BerthEmptier Path Logic:** Entities that travel this path must only have a Priority equal to one (only tankers travel to an emptier). This path is also only active when the Boolean state variable, \( B1\_Switch \), is True which serves as a dynamic switch that can turn on/off the berth mid-execution. If the Boolean state variable, \( SPDS\_Switch \), is also True, there is logic on this path that ensures the tanker first visits the SPDS system.

• **ChannelEntrance to BerthFiller Path Logic:** Entities that travel this path must only have a Priority equal to two (only ships travel to a filler). Other conditions that must be met for this path to be viable are \( B1\_Switch \) must be True, \( B1\_Vacant \) must be True, and the fuel storage tanks that serve the berth must not be empty.

• **ChannelEntrance to SPDSEmptier Path Logic:** Entities that travel this path must only have a Priority equal to one (only tankers travel to an emptier). Other conditions that must be met for this path to be viable are \( SPDS\_Switch \) must be True, \( SPDS\_Vacant \) must be True, and the tanker must not have already traveled to the SPDS system.

• **ChannelEntrance to SPDSFiller Path Logic:** Entities that travel this path must only have a Priority equal to two (only ships travel to a filler). Other conditions that must be met for this path to be viable are \( SPDS\_Switch \) must be True, \( SPDS\_Vacant \) must be True, and the SPDS tank must not be empty.
• **SPDSEmptier to ChannelEntrance Path Logic:** This path will be selected if the refueling berth is open causing the tanker to replenish the port’s fuel supply after visiting the SPDS system.

• **SPDS_Emptier to ExitingTankers Path Logic:** This path is selected if SPDS is the only source of fuel in the port. Tankers will exit the system after replenishing the SPDS tank.

### 3.4 Port Disruption and Resilience Analysis

We define a set of simulation experiments to test the impacts of port disruptions and resilience technologies. We build on the model parameters, measure of performance, and simulation variables from as the Baseline Model with additions relevant for port disruptions, the NFIRRS Model, and the SPDS Model.

#### 3.4.1 Model Parameters

Where possible, disruption and resilience models use the same parameters as the Baseline Model. We also implement the following parameters to include port disruptions in simulation runs:

• **BreakPipe** — When set to `True`, this option introduces a disruption that approximates a break in the fuel pipe that delivers fuel to the port’s berth. Fuel delivery to the berth is not possible until the fuel pipe is repaired. The repair time depends on whether or not NFIRRS is available; if so, the repair time is 1-day, otherwise, the standard repair time without NFIRRS is set to be 7-days.

• **DisableTank** — When set to `True`, this option introduces long-term disruption that approximates a disabled fuel tank that is not capable of being repaired quickly. In a configuration such as our Baseline Port Model, in which there is only one fuel storage tank, fuel delivery at the berth is no longer possible.

We also define a *Disruption Day* parameter for model simulations that determines when disruptions occur. For our analysis, we set this to be the same day as the length of the warm-up period (540 days) to represent a disruption occurring at time $T = 0$ relative to a simulation run.
3.4.2 Measure of Performance

We use the same measure of performance as Equation 3.1. However, we now measure performance for time windows relative to the onset of port disruptions (i.e., the Disruption Day parameter). We adjust the length of each run of the simulation by setting the ‘Run Length’ accordingly. Together with post-disruption statistics (defined below), we are able to observe the cumulative and lasting effects that a disruption has on the average performance of the port.

We also assess the relative impacts of a port disruptions with and without resilience technologies as the system performance with the following equation:

\[
\text{Performance}_{RS} = \frac{\% \text{ Demand Met}^{ND}_{Avg} - \% \text{ Demand Met}^{RS}_{Avg}}{\% \text{ Demand Met}^{ND}_{Avg}} \times 100
\]  

(3.2)

Here, \(\% \text{ Demand Met}^{ND}_{Avg}\) is the mean percent of fuel demand met from 10 simulations of a no disruption scenario and \(\% \text{ Demand Met}^{RS}_{Avg}\) is the mean percent demand met for 10 simulation of a disruption scenario with and without resilience technologies. \(\text{Performance}_{RS} \leq 0\) measures the expected relative impacts of disruptions, where values closer to 0 indicate low impact on port operations and more resilience. \(\text{Performance}_{RS} > 0\) also captures rare cases where port disruptions and/or resilience technologies may improve port operations above those normally expected performance.

3.4.3 Simulation Variables

Port disruption and resilience models use the same simulation variables as the Baseline Model for Ship entity arrivals during non-wartime and wartime conditions. We also define several variables related to the model we choose during a simulation run to account for situations with and without resilience technologies. For setting up Simio experiments, we define the following variables:

- **Resilience Technology:** The type of resilience technology that is available at the port that can be implemented in response to a disruption is selected using a Boolean variable that activates a particular type of resilience technology. The resilience technology options are:
• **SPDS Available:** When set to True, this option enables the implementation of SPDS following a disruption event. This activates an additional refueling with a dedicated underwater fuel storage tank with a capacity of 600,000 gallons. The setup time for SPDS is 48 hours following the disruption.

• **NFIRRS Available:** When set to True, this option enables the implementation of NFIRRS following a disruption event. This reduces the repair time following a damaged pipe from 7-days to 1-day.

Using these parameters, MOP, and variables, we are able to assess the impact of port disruptions and the benefits of resilience technologies. We present these results in the next chapter and compare these simulations to the Baseline Model simulations without disruptions (Figures 3.3 and 3.4).
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CHAPTER 4: Results

In this chapter, we analyze the impact that port disruptions have under a normal scenario and a wartime scenario for our Baseline Model. We then implement resilience technologies, specifically NFIRRS and SPDS, under the same conditions to assess the benefits that they provide in terms of overall port performance.

4.1 Impacts of Disruptions and Resilience Technologies

In this section, we begin by analyzing the performance of the port subject to a disruption. We then implement resilience technologies (NFIRRS and SPDS) to assess their effect on the port’s ability to meet incoming fuel demand. Finally, we conclude by comparing the two resilience technologies and determining the situations in which one technology might be better than the other.

4.1.1 Normal port disruption

During the non-wartime scenario shown in Figure 4.1, for the 14-day time window, compared to the non-disrupted case, we see the impact of a disruption having up to a 44.2% drop in mean percent demand met, with a 95% confidence interval (CI) of (40.9, 47.5). The impact is most pronounced at the shorter time-windows and the average port performance steadily improves when looking at post disruption time-windows of increasing size. However, even compared to the non-disrupted scenario at 180 days, the port is never able to reach the average port performance, still showing a 4.4% drop in performance, with a 95% CI of (2.0, 6.8).

For the wartime scenario depicted in Figure 4.2, we see very similar results to the non-wartime scenario. There is a greater impact seen at the 14 day time-window with a 49.0% drop in percent demand met, with a 95% CI of (44.9, 53.0). As in the non-wartime case, things steadily improve over time; however, even compared to the non-disrupted scenario at 180 days, there is still a 4.1% drop in performance, with a 95% CI of (1.5, 6.7).
Figure 4.1. Disruption Impact (Non-Wartime SAG Arrival Rate). The impact of a disruption repaired in 7 days (orange) is compared against no disruption (blue). The result is up to a 44.2% drop in the port’s ability to meet the incoming fuel demand (14-day time window), with a 95% CI of (40.9, 47.5). The cumulative effects of this 7-day disruption on average port performance last for over six months after the disruption.

Figure 4.2. Disruption Impact (Wartime SAG Arrival Rate). The impact of a disruption that is repaired in 7 days (orange) is compared against no disruption (blue). The result is up to a 49.0% drop in the port’s ability to meet the incoming fuel demand (14-day time window), with a 95% CI of (44.9, 53.0). Additionally, the cumulative effects of this 7-day disruption on average port performance last for over six months after the disruption.
4.1.2 Benefits of NFIRRS

We now assess the benefits that NFIRRS provides by examining port performance under the same non-wartime and wartime scenarios. We assume that NFIRRS provides a 1-day repair time (versus the normal 7-days), and we assume that NFIRRS restores the port to pre-disruption conditions.

For the non-wartime scenario shown in Figure 4.3, we see that NFIRRS provides a significant improvement over the normal 7-day repair time case in terms of reduced impact of the disruption as well as faster recovery to pre-disruption levels of average cumulative port performance. Again, we see the maximum impact on cumulative average port performance when looking at the 14-day post-disruption time window; however, this drop is only 8.0%, with a 95% CI of (3.9, 12.1), compared to the 44.2% drop seen with the normal 7-day repair time. By 30 days, we only see a 2.2% drop in percent demand met, with a 95% CI of (-0.9, 5.3), compared to the non-disrupted case, and by 180 days it is down to just 0.5%, with a 95% CI of (-1.8, 2.8). We see that having the faster repair time provided by NFIRRS allows the port to rebound quickly and perform essentially the same as in the non-disrupted case. Likewise, the cumulative impacts on average port performance over time are drastically reduced or even eliminated.

For the wartime scenario depicted in Figure 4.4, we see that NFIRRS offers significant improvement across the board when compared to the normal 7-day repair time case in terms of average cumulative port performance. We see that NFIRRS roughly cuts the impact on percent of fuel demand met in half at every post-disruption time window. By 180 days, cumulative average port performance is within 1.9% of the performance of the non-disrupted port, with a 95% CI of (-0.8, 4.7).
Figure 4.3. Benefits of NFIRRS (Non-Wartime SAG Arrival Rate). The impact of NFIRRS (gray) is compared to a 7-day repair time (orange) as well as a port with no disruption (blue) in a non-wartime scenario. Here, NFIRRS provides significant reduction in the impact of the disruption as well as fast recovery to pre-disruption performance levels.

Figure 4.4. Benefits of NFIRRS (Wartime SAG Arrival Rate). The impact of NFIRRS (gray) is compared to a 7-day repair time (orange) as well as a port with no disruption (blue) in a wartime scenario. Here, NFIRRS cuts the drop in average percent demand met roughly in half at every post-disruption time window.
4.1.3 Benefits of SPDS

We now assess the benefits that SPDS provides by examining port performance under the same non-wartime and wartime scenarios. We assume that SPDS is setup and available 48 hours after the disruption, and we assume that the 600,000 gallon SPDS fuel tank is full when SPDS is setup and ready for use. We assess the performance of SPDS under two situations: 1) SPDS without repair of the original disruption over the entire 180 days, and 2) SPDS in conjunction with the normal 7-day repair time of the disruption.

SPDS without Repair

In this situation, we assume that the disruption to the port is never repaired within the 180 days, the port’s refueling berth is not re-opened, and that all ships are refueled at the SPDS system that is made available within 48 hours after the disruption.

For the non-wartime scenario shown in Figure 4.5, we see that SPDS without repair offers considerable reduction in impact due to the disruption even when compared to the normal repair case for time windows 30 days and below. For the 14-day time window, we see a 17.7% drop in average percent demand met, with a 95% CI of (14.1, 21.3), compared to the 44.2% drop seen in the normal repair scenario. For the 30-day window, we see a 13.4% drop in average percent demand met, with a 95% CI of (10.2, 16.6), compared to a 24.2% drop. However, beyond 30 days, we see the percent demand met of this system plateau at levels approximately 12.7% below the non-disrupted case, with a 95% CI of (9.3, 16.2)—this is due to the fact that the port is now operating with a reduced fuel storage capacity and reduced fuel delivery rates. Though in this case, it demonstrates the benefit that SPDS can offer in situations in which timely port repair is not possible, allowing the port to provide sustained, but limited, performance.

For the wartime scenario depicted in Figure 4.6, again we see that SPDS without repair offers improvement in the short-term in terms of reduction in impact due to the disruption; however, in this case the benefit of over the normal repair case is no longer present at 30 days and beyond. Here we see the performance of this system plateau at levels approximately 17.5% below those of the non-disrupted port, with a 95% CI of (15.3, 19.7).
Figure 4.5. Benefits of SPDS without Repair (Non-Wartime SAG Arrival). The impact of SPDS without repair (yellow) is compared to a 7-day repair time (orange) as well as no disruption (blue) in a non-wartime scenario. SPDS provides a reduction in the impact of the disruption for the short-term (14 days and 30 days). Beyond 30 days, we see system performance plateau at 12.7% below the non-disrupted case, with a 95% CI of (9.3, 16.2).

Figure 4.6. Benefits of SPDS without Repair (Wartime SAG Arrival). The impact of SPDS without repair (yellow) is compared to a 7-day repair time (orange) as well as a port with no disruption (blue) in a wartime scenario. SPDS provides a benefit over the normal repair case in the 14 day window. System performance plateaus at levels approximately 17.5% below that of the non-disrupted port, with a 95% CI of (15.3, 19.7).
**SPDS with Normal 7-day Repair**

In this situation, we assume that the disruption to the port is repaired after 7 days and that the port’s refueling operations return to pre-disruption conditions with the additional benefit of having SPDS implemented at the port.

For the non-wartime scenario shown in Figure 4.7, we see that SPDS with repair offers considerable recovery in the short-term (14 day time window) when compared to the non-disrupted case, with only an 11.9% drop in average percent demand met, with a 95% CI of (-0.8, 4.7); this is compared to the 44.2% drop that is seen in the 7-day repair case without SPDS. For time windows of 30 days and above, the SPDS with repair case actually outperforms the non-disrupted port. By 180 days, this configuration of the port actually provides a 5.2% increase in percent demand met over the non-disrupted port, with a 95% CI of (5.6, 10.4).

For the wartime scenario depicted in Figure 4.8, again we see that SPDS with repair offers improvement in the very short-term (14 day time window) in terms of average percent demand met when compared against the normal repair case. In this scenario, we start to see the benefits of the additional port capacity by the 90 day mark, which is the time window that this configuration starts to outperform even the non-disrupted port. By 180 days, this configuration outperforms the non-disrupted case by 8.0%.
Figure 4.7. Benefits of SPDS with Repair (Non-Wartime SAG Arrival). The impact of SPDS with repair (light-blue) is compared to a 7-day repair time (orange) as well as a port with no disruption (blue) in a non-wartime scenario. Here, SPDS provides quick recovery as well as improved performance even over the non-disrupted port.

Figure 4.8. Benefits of SPDS with Repair (Wartime SAG Arrival). The impact of SPDS with repair (light-blue) is compared to a 7-day repair time (orange) as well as a port with no disruption (blue) in a wartime scenario. Here, SPDS provides quick recovery as well as improved performance even over the non-disrupted port.
4.2 Comparison of Resilience Technologies

In this section we compare the results that were obtained individually in the previous sections, this time looking at the average benefits of each technology relative to no-disruption. Tables 4.1 and 4.2 show the percent change in mean performance relative to the no-disruption scenario (Equation 3.2). From these tables we see that NFIRRS and SPDS are both capable of providing resilience to ports experiencing disruption of this kind. However, we find that each technology provides resilience in its own unique way that can be characterized into one of the four categories of resilience: 1) robustness, 2) rebound, 3) extensibility and 4) adaptability (Woods 2015).

Table 4.1. Percent Demand Met Relative to No Disruption (Non-Wartime).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>14 days</th>
<th>30 days</th>
<th>60 days</th>
<th>90 days</th>
<th>120 days</th>
<th>180 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Repair</td>
<td>-50.9%</td>
<td>-28.6%</td>
<td>-16.2%</td>
<td>-10.1%</td>
<td>-7.8%</td>
<td>-4.9%</td>
</tr>
<tr>
<td>NFIRRS Repair</td>
<td>-9.3%</td>
<td>-2.6%</td>
<td>-1.7%</td>
<td>-1.4%</td>
<td>-0.9%</td>
<td>-0.6%</td>
</tr>
<tr>
<td>SPDS + No Repair</td>
<td>-20.4%</td>
<td>-15.8%</td>
<td>-17.8%</td>
<td>-15.8%</td>
<td>-13.8%</td>
<td>-14.1%</td>
</tr>
<tr>
<td>SPDS + Repair</td>
<td>-13.7%</td>
<td>3.4%</td>
<td>0.2%</td>
<td>3.7%</td>
<td>5.6%</td>
<td>5.8%</td>
</tr>
</tbody>
</table>

In a non-wartime scenario, we see that NFIRRS provides fast restoration and rebound to the system. Here, we see that NFIRRS nearly eliminates the impact that the disruption has on port refueling operations. By 30 days, the cumulative impact of the disruption on average port performance is only 2.6% lower than the non-disrupted case, and by 180 days, that reduces to a 0.6% drop in performance. SPDS without repair offers some recovery in the form of adaptability, resulting in operations being shifted to a completely different system, but we see that SPDS alone ultimately results in a 14.1% drop in performance by 180 days due to the port having a reduced capacity when compared to its original configuration. Finally, we see that SPDS plus repair not only provides an immediate benefit, with only a 13.7% drop in performance at 14 days, but it also results in a system that eventually outperforms the original system, resulting a 5.8% increase in performance relative to the non-disrupted port. This is an extensibility approach to resilience, as the original disruption is repaired in conjunction with the deployment of a new system.
Table 4.2. Percent Demand Met Relative to No Disruption (Wartime).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>14 days</th>
<th>30 days</th>
<th>60 days</th>
<th>90 days</th>
<th>120 days</th>
<th>180 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Repair</td>
<td>-55.6%</td>
<td>-30.3%</td>
<td>-16.4%</td>
<td>-10.9%</td>
<td>-8.3%</td>
<td>-5.2%</td>
</tr>
<tr>
<td>NFIRRS Repair</td>
<td>-29.1%</td>
<td>-15.7%</td>
<td>-8.2%</td>
<td>-5.4%</td>
<td>-3.9%</td>
<td>-2.4%</td>
</tr>
<tr>
<td>SPDS + No Repair</td>
<td>-25.0%</td>
<td>-28.0%</td>
<td>-28.7%</td>
<td>-23.5%</td>
<td>-24.6%</td>
<td>-22.1%</td>
</tr>
<tr>
<td>SPDS + Repair</td>
<td>-19.4%</td>
<td>-30.4%</td>
<td>-5.2%</td>
<td>3.9%</td>
<td>6.4%</td>
<td>10.1%</td>
</tr>
</tbody>
</table>

We see similar results, with some key differences, in our analysis of the wartime scenario in Table 4.2. Here, NFIRRS continues to provide timely rebound for the system in the medium to long term time windows; however, in the immediate near-term (14 days), it is outperformed by the other resilience technologies. We see that in wartime SPDS without repair maintains its ability to offer continued but limited port refueling capability, resulting in performance that is approximately 22–25% below non-disrupted levels. And again, SPDS with repair manages to provide immediate benefit, while also resulting better port refueling operations in the long term, or 10.1% above non-disrupted performance at 180 days.

Neither resilience technology performs conclusively better than the other in each case; instead, they both offer unique benefits depending on the scenario. An example of this is the wartime scenario in which NFIRRS is outperformed by both implementations of SPDS in the 14-day time frame; however, NFIRRS then outperforms SPDS during the 30-day time frame. This result is attributed to the additional system complexity that comes with SPDS, which results in a new system configuration that is more complex to manage and one that takes longer to reach steady-state. In this case, NFIRRS does not provide the same long term benefits as that of SPDS with repair. However, if naval operations are depending on a 30-day planning window, NFIRRS might offer the greatest benefit.
CHAPTER 5:  
Conclusion

Ports in the Indo-Pacific region provide critical refueling capabilities to our fleet that enable uninterrupted military operations and power projection throughout the region. In a future conflict with a near-peer adversary like China or Russia, these critical ports present tempting targets, making them highly vulnerable. There are many different technologies in development across several organizations within the USN that augment the resilience of port refueling infrastructure; however, there is not enough work being done to compare these technologies to better understand when and where certain technologies should be used instead of another.

5.1 Thesis Summary

The first task of this thesis was to develop a framework for assessing port refueling operations. We chose to use discrete event simulation due to the complexity and the dynamic nature of port refueling operations, especially when given disruptions. We used Simio to develop the discrete event simulation using objects from Simio’s Standard and Flow libraries—using a combination of container entities, emptiers, fillers, and tanks combined with complex routing logic and add-on processes, we developed a framework that allows us to model any commercial or non-commercial port. We use these pieces to model a simple port consisting of a single channel entrance, single refueling berth, and a single fuel storage tank. We analyze this simple port’s refueling operations in a permissive (non-wartime) and wartime environment in order to better understand the impacts each situation has on average port performance over time. Our wartime scenario is modeled as a surge in SAG arrivals, representing an increased war effort or war activity in the region where the port is located.

The other benefit of this framework is that it not only allows us to just study how ports work, but it also allows us to study the impact that disruptions have on port operations. We study the impact of a simple port disruption lasting 7 days—we expect this disruption period to be consistent with a typical Indo-Pacific port disruption given the scarcity of equipment and repair supplies in the region. Results for this simple port disruption led to near-term and long-term impacts on refueling operations. The results show that even in
a non-wartime scenario, the 7-day disruption can lead to a significant reduction in total demand met for refueling operations over the first few weeks following a disruption, and although the effect on refueling operations is short, we see a long-term impact on the average refueling performance—resulting in periods of 4–6 months before getting back to pre-disruption average performance levels.

We find the technologies developed by NAVFAC EXWC and NAVSEA OPLOG to be capable of providing resilience to ports experiencing disruption of this kind. Resilience as described earlier in this thesis is characterized in four different ways: 1) robustness, 2) rebound, 3) extensibility and 4) adaptability (Woods 2015). Each resilience technology scenario emphasizes a different kind of resilience. NFIRRS provides fast restoration or rebound to the system. In a non-wartime scenario, NFIRRS nearly eliminates the impact that the disruption has on port refueling operations. However, during our wartime scenario with a surge in arriving ships, NFIRRS appears to be less efficient in the immediate near-term and long-term compared to other resilience technologies.

In contrast, SPDS without repair offers an adaptability approach to resilience, resulting in operations being shifted to an entirely new system. We see that this does reduce the overall impact of the disruption, but it leads to a long term drop in performance due to the port having reduced capacity compared to the original port configuration.

Finally, SPDS with repair offers an extensibility approach to resilience, where the port disruption is repaired in conjunction with the deployment of the new system. This configuration not only provides immediate benefit in response to a disruption, but it also leads to better port operations in the long term.

It is important to note that neither technology, NFIRRS or SPDS, was better than the other; instead, they offered unique benefits over the other in specific scenarios. For example, NFIRRS (rebound) did not outperform either implementation of SPDS (extensibility and adaptability) in the 14-day time frame during a wartime scenario. However, NFIRRS outperforms both implementations of SPDS during the 30-day time frame in the same wartime scenario. This is due the fact that the extensibility and adaptability options result in new system configurations that are more complex to manage and take longer to reach steady-state than the original port configuration. NFIRRS does not provide the same long term benefits as that of SPDS with repair. However, if naval operations are depending on a
30-day planning window, NFIRRS might offer the greatest benefit.

Overall, we recommend that the Navy invests in both NFIRRS and SPDS. NFIRRS is easy to deploy and relatively low cost compared to SPDS, and NFIRRS is best suited for non-wartime scenarios and ports that we don’t anticipate requiring additional support during wartime. In contrast, SPDS with repair provides new capacity to extend operations in the long term which leads to better port operations for smaller ports that may need additional capacity during wartime. On its own, SPDS without repair can help manage and mitigate the impacts of disruptions even when timely port repair efforts are not possible. Deploying SPDS in regions that we anticipate the need for wartime refueling efforts is a critical next step.

5.2 Limitations and Areas for Future Work

This thesis only studied NFIRRS and SPDS, but there are at least 3 other resilience technologies mentioned in Table 3.1 that we did not study. Stakeholder elicitation identified upwards of 24 more technologies related to naval distributed refueling being developed by various organizations within the USN not mentioned here. Although some of these are suited for aircraft refueling, many of them might also offer resilience solutions for port refueling operations. Before the Navy commits to making large investments in the two technologies that we studied, we recommend that models are developed that implement these other applicable technologies.

We measured the benefit of NFIRRS and SPDS using a simple port configuration consisting of one refueling berth, one fuel storage tank, one primary fuel pipe, and a single channel entrance to the port. Future work could apply the framework developed in this thesis to model the true configuration of an actual port in the Indo-Pacific region. We anticipate actual ports to have a more complex fuel piping system and multiple fuel storage tanks that could change the need or deployment of resilience technologies because the potential for disruption could be much lower due to the higher reliability and presence of more backup systems.

This research did not consider the combined effects of multiple resilience technologies (e.g., a port with both NFIRRS and SPDS available). We anticipate the results of combined technologies to be even better in terms of port performance than those provided by the
technologies individually, but if more than two technologies were modeled, future work could explore the optimal combination of technologies for managing and responding to port disruptions.

Future work could consider technologies that improve port resilience via robustness. Although the technologies that we studied in this thesis mainly provided rebound, extensibility, and adaptability forms of resilience, there has been significant work on the hardening and protection of critical port refueling infrastructure. Including the effects of robustness technologies, such as underground or hardened fuel tanks, would be beneficial for understanding cost benefit of NFIRRS and SPDS against other forms of mitigation.

Future extensions of our framework could be adapted to implement aircraft refueling operations and the respective resilience technologies that are in development for aircraft refueling. This adaptation would utilize many of the same modeling objects as used in our port model due to the analogous nature of the two activities—both systems involve arriving entities requiring fuel, entities are routed to a refueling location, refueling occurs, and finally the entity exits the system.

SPDS is capable of being connected to the tanks on land, but this requires additional time and is more difficult to implement. This might lead to better port operations by allowing ships at SPDS to access fuel on land. It allows the repaired system to act as an better integrated port. However, this implementation would take longer to initially install, slowing recovery time immediately after a disruption. Future work could implement this configuration of SPDS and evaluate the benefits and trade-offs its use.

Other areas for future work could explore the pre-deployment of technologies. SPDS in particular, can be deployed prior to a disruption, rather than in response to one. There can be additional studies that can consider how many days before a disaster one would want to deploy SPDS to avoid major disruptions.
List of References


Kotachi MA (2018) Sequence-based simulation-optimization framework with application to port operations at multimodal container terminals.


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