SIMULATING MARITIME CHOKEPOINT DISRUPTION IN THE GLOBAL FOOD SUPPLY

THESIS

Ryan B. Walton, Captain, USAF

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DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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Ryan B. Walton, BA

Captain, USAF

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Ryan B. Walton, BA
Captain, USAF

Committee Membership:

Dr. J.O. Miller, PhD
Advisor

Dr. Lance E. Champagne, PhD
Reader

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Abstract

The three food crops of wheat, maize, and rice make up almost two-thirds of the world's dietary energy needs. Of these three, just six countries provide 70% of the global supply. Furthermore, soybeans account for three-quarters of global livestock feed, and only three countries provide 80% of the global supply. Considering over half of the world's exported supply of these four commodities are exported via maritime means, the free flow of marine traffic becomes paramount. Current models lack the ability to capture the inherent variance displayed in the maritime transport system, which can lead to inaccurate assumptions about how the system functions - assumptions that could ultimately bring chaos to an importing economy.

To capture this inherent variance, a discrete-event simulation was built to better understand how disruptions in this system impact those who rely on its unhindered functionality. Monthly export data is used, and the maritime chokepoints of the Panama Canal, the Suez Canal, and the Strait of Gibraltar are modeled for disruption.

Results indicate significant food shortages for all importers studied, with some receiving 97% less of a commodity in a given month. China is particularly sensitive to a closure of the Panama Canal in the months of September - January. Egypt and Spain could expect significant food decreases if the Strait of Gibraltar were to close in any month, with Spain experiencing its worst declines should a disruption occur in September. Marine traffic through the Strait of Malacca was also significantly impacted when any of the three chokepoints studied were closed.

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To my wife, for without you none of this would have been possible. I love you.

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Ryan B. Walton

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Acronyms

Acronym	**Definition**
CA	Cellular Automata
CSAF	Chief of Staff of the Air Force
EIA	United States Energy Information Administration

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SIMULATING MARITIME CHOKEPOINT DISRUPTION IN THE GLOBAL FOOD SUPPLY

I. Introduction

1.1 Background

Every year, the Chief of Staff of the Air Force publishes his or her Professional Reading List. This reading list "provides a range of professional development opportunities to refocus our thinking on the challenges that this new era brings" (Goldfein, 2017). In 2017, Chief of Staff of the Air Force (CSAF) General David L. Goldfein added The Accidental Superpower by Peter Zeihan to his yearly list. Specifically, the CSAF Professional Reading List (2017) offered the following concerning the General's choice:

> The global security environment is evolving faster than any of us can fathom, and in the coming century America will be challenged across the spectrum of conflict in ways we cannot imagine. We must have Airmen leading our force who can quickly and deliberately synthesize a number of competing theories on the current and future state of global affairs. This book provides a glimpse [of] one of these possible futures, where our nation will find itself confronting a world where the global systems as we know them rapidly evolve in the face of relentless change.

The book's full title, "The Accidental Superpower: The Next Generation of American Preeminence and the Coming Global Disorder," is predominately concerned with analyzing the variables that led to the rise of nations as we know them today, then forecasts their paths forward (Zeihan, 2014). According to the author, these paths are determined by a nation's geography, political climate, and demography. The author's assessments are compelling, if not startling. Then, perhaps coincidentally, the U.S. Army Chief of Staff General Mark A. Milley added Zeihan's book to his 2017 Professional Reading List as well.

The rise of globalization and the global economy is irrefutable – the world is now more connected than ever. Never has there been an age where nations depended so heavily on other nations for their survival. According to the U.S. Energy Information Administration (2018), Saudi Arabia was the world's second highest producer of Total Petroleum and Other Liquids products, producing 12% of the world's total in 2017 (the United States was first at nearly 16%). These vast oil reserves have made Saudi Arabia quite rich. In a time when millions of barrels of oil are required every day by every developed country in the world in order to simply keep the lights on, this gives Saudi Arabia a power money cannot buy. The developed world knows oil is a requirement for survival.

However, oil is just a resource. It's simply an input. Merriam-Webster Online (2019) defines a resource as "a natural feature or phenomenon that enhances the quality of human life." Yes, oil certainly does enhance the quality of human life, but the definition implies oil is not a requirement for human life – it's only there to "enhance." What then, if not oil, would be a resource that's a requirement for human life? One answer is food, which can be captured in a model using a representative set of cereals and soybeans (Jones and Ejeta, 2016; Wellesley et al., 2017).

Unless a food-importing country borders a food-exporting country, foodstuffs will most likely be shipped via maritime means. Maritime shipping is cheap and can accommodate large amounts of product, which makes it an ideal transportation mode even if countries border each other. Figure 1 depicts maritime shipping routes recorded in May 2012:

Figure 1. Eurasia Maritime Shipping Routes (Kiln, 2019)

As can be seen in Figure 1, the only routes ships do not take are ones with draft requirements (the water is too shallow). Other than draft, ships can essentially navigate the globe unrestricted, traveling the shortest most direct route to save time and money. However, these routes often pass through global maritime chokepoints. Merriam-Webster Online (2019) defines a chokepoint as "a strategic narrow route providing passage through or to another region." In the case of maritime shipping, these chokepoints connect one geographic body of water to another. The disruption of the free flow of global cereals and soybeans through these chokepoints is the focus of this paper.

1.2 Problem Statement

To understand the relationship between global maritime chokepoints and a country's level of food security, the current maritime transportation system must be considered. This research uses historical data inside the simulation software Simio to model the maritime transportation system of cereals and soybeans through different maritime chokepoints. Results from this simulation model are analyzed to determine the impact a disruption of maritime chokepoints has on the global supply of cereals and soybeans.

1.3 Scope

The world's population is growing at an alarming rate, with each person requiring food to survive. As countries grow, many cannot feed their citizens purely from within and must reach out beyond their borders. According to Bailey and Wellesley (2017), each year 2.8 billion people are fed via the global transport system. Maize, rice, and wheat make up almost two-thirds of the world's caloric needs (Jones and Ejeta, 2016). Of these, only six countries provide 70% of the global supply. Furthermore, soybeans account for three-quarters of global livestock feed, and only three countries provide 80% of the global supply (Wellesley et al., 2017). Over half of these foods are shipped over water and pass through maritime chokepoints, exposing an importing country to increased risk of weather-related delays, piracy, and terrorism.

This research seeks to analyze seasonal maritime chokepoint risk in the global transportation system of cereals and soybeans. Thus, a simulated abstraction of the global maritime shipping system is needed so that seasonal risk can be quantified and further understood.

1.4 Simulations of Maritime Transportation

Given the global use of maritime shipping and its importance to economic well–being, the modeling of maritime networks is a frequent endeavor. Specifically, concerning the variation introduced by weather, ship speeds, and varying crop yields, simulation has been the preferred analytic method of choice to capture this variability. Qu and Meng (2012) used a Cellular Automata (CA) simulation model in conjunction with a discrete-event simulation to simulate ship movements through the Singapore Strait. According to the authors, CA models are capable of capturing complex driving behavior and have been used previously in modeling roadway traffic, discretizing traffic lanes into small cells with vehicles moving from cell to cell based on a pre-defined velocity. The authors then used discrete-event simulation to model random events such as arrivals, weather, wind, sea current, and tide.

Caris et al. (2011) developed a discrete-event simulation to model alternative transport options for container barges in the port area of Antwerp. The author's analysis was mainly concerned with the impact different hub scenarios had on waiting times and turnaround times for vessels within the port area. Furthermore, Smith et al. (2009) modeled ship congestion in the Upper Mississippi River with a discrete-event simulation, using entities to represent six different classes of ships. The authors focused on vessel movements and lock operations in the river system, examining ship activities under a wide range of operating conditions.

Concerning global chokepoints, Köse et al. (2003) used a discrete-event simulation to model ship traffic flowing through the Istanbul Strait (part of the Turkish Straits). The Istanbul strait links the Black Sea with the Sea of Marmara, and is a mere 698m wide at its narrowest point making it the world's narrowest Strait. The authors modeled ships as entities and considered various sizes of ships and the impact of bad weather conditions – both of which can reduce the flow of traffic to one-direction or close the Strait completely. Various scenarios were then considered, including varying ship arrival and waiting times at the headwaters. Simulation results found that an increase of ship arrivals of just 36% to the Strait causes ship waiting times to jump from a mere 16 minutes to 918 minutes. Mavrakis and Kontinakis (2008) built a similar discrete-event simulation to model maritime traffic through the Strait as well and arrived at similar results.

Based upon studies such as those presented here, the use of discrete-event simulation provides a proven approach to explore the many different factors that influence this type of system.

1.5 Methodology

Moving food via maritime means requires the study and use of the global maritime transport system. Transport system terminology, however, is divided among authors, and often depends on geography and traffic mode (Woxenius, 2007). Therefore, the generic framework provided by Woxenius (2007) is used. Six generic transportation system designs are considered for this model: direct link, corridor, hub-and-spoke, connected hubs, static routes, and dynamic routes. Figure 2 enumerates these six designs, providing routes from the Origin (O) to the Destination (D):

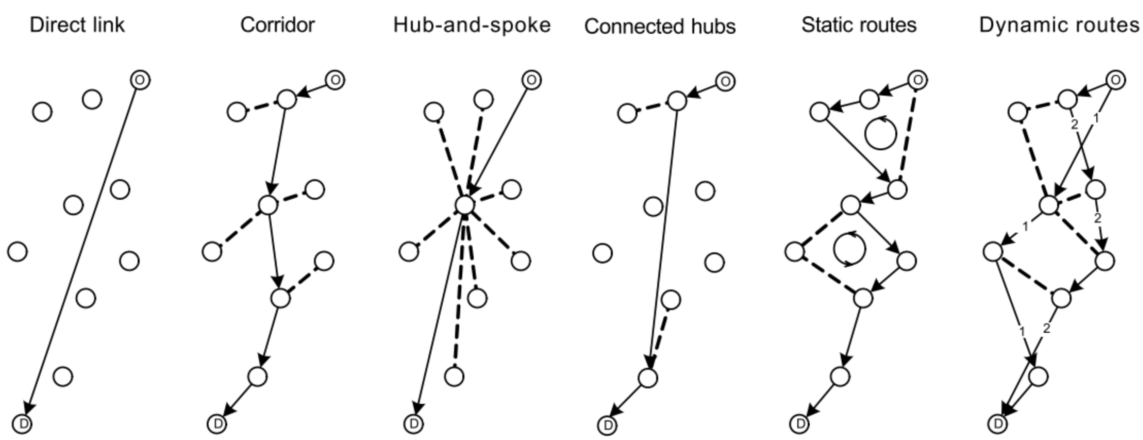

Figure 2. Transport Network Designs (Woxenius, 2007)

The direct link approach simply provides a direct route from origin to destination, with no coordination or visitation with any nodes in-between (Woxenius, 2007). A real-world maritime example of this design would be the travel between two inward-facing ports, where each port has open line-of-sight of the other. A ship traveling from one port to the other can travel on a straight line to its destination.

The connected hubs design can be considered a direct-link design with regional consolidation, meaning hubs on the route can still be bypassed if there is a more direct route available. However, instead of a direct route being taken from origin to destination, a regional hub must first be visited to reach the destination (Woxenius, 2007). Considering maritime transport, this design would be used when no direct line-of-sight is available between ports.

The last design considered is the dynamic routes design. Dynamic routes are determined in real-time and depend on the current transport environment. Given the circumstances of real-world events, any combination of hubs may be visited from origin to destination - whichever combination of hubs providing the best option at the time would be chosen. Dynamic routes provide maximum flexibility in route planning (Woxenius, 2007). Considering maritime transport again, dynamic routes would be considered when the ocean travel environment is constantly changing. For example, if a ship's route includes a visit to a hub as it proceeds to its destination and the hub is subsequently closed, the ship must dynamically find an alternate route to avoid this closed hub. For purposes of this model, a combination of direct link, connected hubs, and dynamic routes is used.

According to Qu and Meng (2012), a simulation of ship movement should contain four elements: a ship, the location of a ship, the speed of a ship, and finally a time aspect. These elements are used in designing the simulation for this study. Every ship in this discrete-event simulation is an entity carrying a certain amount of either maize, wheat, or soybeans. Ships also receive a speed and final location. Once a final location is given, a route is assigned that minimizes total distance traveled.

To model location, Simio utilizes a framework known as a geographic information system (GIS). This framework provides the capability of inserting a drawn-to-scale background map of the entire world. This allows the modeler to place objects at exact lat–long coordinates, and also provides accurate distance calculations between two points. It is then possible to have entities move from one location to another using the exact real–world distance.

Speed is modeled using a triangular distribution, based on real-world data using a mode, high, and low speed. Once assigned, the speed of the ship does not change. Time is represented by a system clock with simulated events occurring at discrete points in time.

1.6 Outline

Chapter 2 provides additional details on further maritime transportation research, model development, and analytical results. Chapter 3 is a real–world application of the model. Chapter 4 concludes this thesis by discussing significant findings and recommendations for further research. Chapters 2 and 3 are structured as an individual journal paper and conference proceeding, respectively.

II. Simulating Maritime Chokepoint Disruption in the Global Food Supply

2.1 Introduction

Only three food crops (maize, rice, and wheat) make up almost two-thirds of the world's dietary energy needs (Jones and Ejeta, 2016). Of these three cereals, just six countries provide 70% of the global supply. Furthermore, soybeans account for three-quarters of global livestock feed, and only three countries provide 80% of the global supply (Wellesley et al., 2017). These four megacrops are the backbone of the global food supply. Figure 3 details the top countries producing these crops.

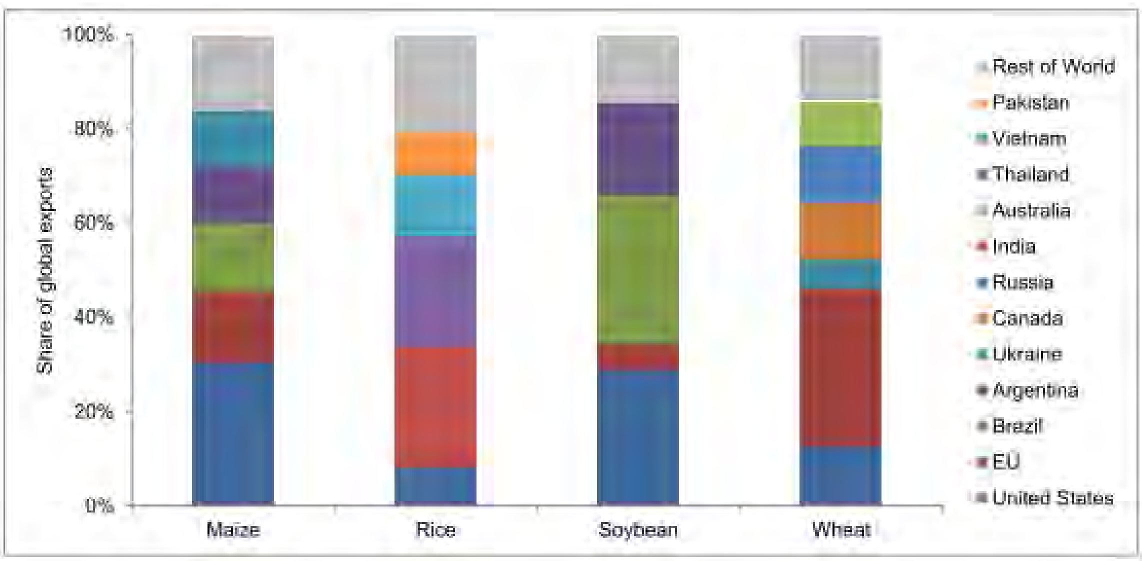

Figure 3. Global Cereal and Soybean Producers (Wellesley et al., 2017)

The worlds population is now over seven billion people and growing, each one requiring food to survive. Many countries have populations that are too large to feed with locally-sourced food and must reach out beyond their borders to feed their citizens. According to Bailey and Wellesley (2017), 2.8 billion people are fed via the global transport system each year. Assuming a population of seven billion people in the world, this equates to 40% of the world's population is reliant on global transport to meet their daily caloric needs.

Given the global requirement for imported food, transportation becomes important. A large proportion of the world's traded cereals and soybeans are shipped via maritime means (Bailey and Wellesley, 2017). Once loaded, these ships follow accepted maritime shipping routes, as shown in Figure 4.

Figure 4. Eurasia Maritime Shipping Routes - Background Removed (Kiln, 2019)

As can be seen in Figure 4, larger amounts of ship activity indicate where global populations might reside or is on the way, as evidenced by the thicker brighter concentrations (for example, the brightness of China's eastern coast).

However, bright spots away from global population centers indicate ships on their respective shipping routes. In some instances, thicker concentrations indicate direct point-to-point movement, saving both time and money. In others, however, these concentrations indicate the presence of global chokepoints.

Chokepoint analysis to date has mostly been concerned with the free flow of the global oil supply. According to the U.S Energy Information Administration (EIA), "chokepoints are a critical part of global energy security because of the high volume of petroleum and other liquids transported through their narrow straits," and EIA has declared seven global chokepoints for global seaborne oil transportation. These oil chokepoints are the Strait of Hormuz, Strait of Malacca, the Suez Canal, Bab el-Mandeb, the Danish Straits, the Turkish Straits, and the Panama Canal. The U.S. EIA also includes the Cape of Good Hope as it is part of a major trading route and is an alternative route to other chokepoints (U.S. Energy Information Administration, 2018).

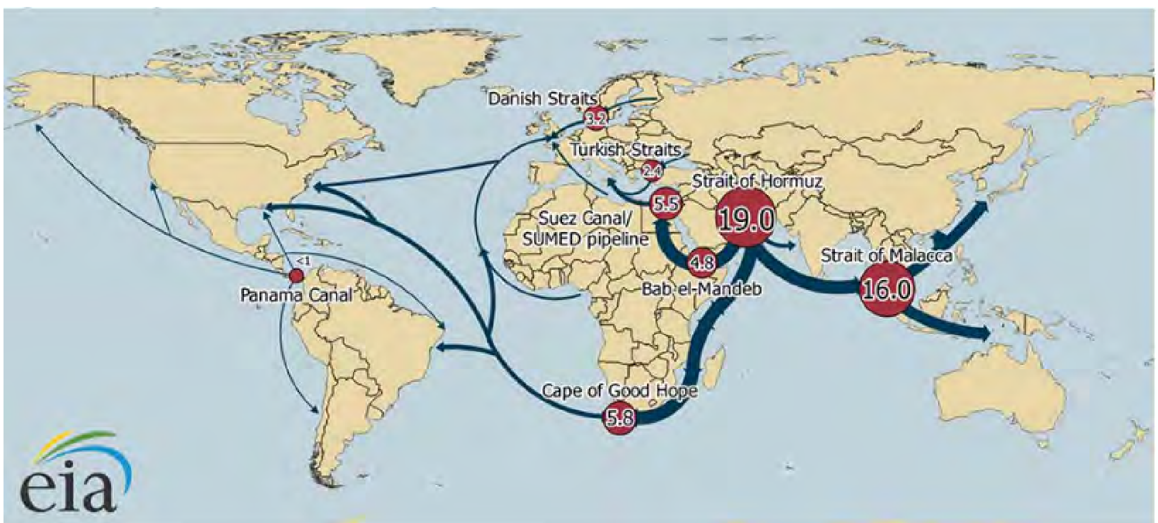

Figure 5. Major Oil Routes and Chokepoints (U.S. Energy Information Administration, 2018)

For example, if Europe desired to trade with China (as it often does), then a ship traveling from Europe would have to pass through the Strait of Gibraltar (depending on which country in Europe the cargo originated), the Suez Canal, Bab-el-Mandeb, the Straits of Malacca, and the South China Sea. In total, five global chokepoints must be traversed before a ship traveling from Europe can reach China. Alternatively, a route including the Cape of Good Hope (a route around the southern-most tip of

Africa) is feasible and would reduce the number of chokepoints traversed, but if one considers the Cape of Good Hope as a global chokepoint, this route only reduces the number of global chokepoints traversed by one. It also greatly increases the distance and time of voyage. Figure 6 highlights both traditional and non-traditional global maritime chokepoints.

Figure 6. Traditional Global Chokepoints (Wellesley et al., 2017)

Traveling on a route that includes maritime chokepoints is not necessarily bad - the route is often shorter and allows shipping companies to reduce costs and save time. However, for nations that depend on imported food to survive, disruptions to these chokepoints could quickly become a national security issue.

2.2 Overview

Transportation risk has been widely studied in the case of the global oil supply chain, as roughly 61% of the worlds traded oil supply was shipped via maritime means in 2015. In the event of a chokepoint disruption, energy costs and world oil prices could increase substantially. Idle tankers would also be left vulnerable to pirate, terrorist, or hostile nation attacks (U.S. Energy Information Administration, 2014). Between 1991 - 2001, 66% of the worlds piracy attacks occurred in the Straits of Malacca. In 2008, Somali pirates hijacked a Saudi Arabia-owned supertanker 450 miles southeast of Mombasa, Kenya (Wu et al., 2009). Piracy is a growing concern, and the future of maritime shipping indicates no slowing of volatility in the industry (Viljoen and Joubert, 2016).

Piracy, however, is typically conducted by non-state actors. Throughout history, Iran has repeatedly threatened to close the Strait of Hormuz, with its most recent threat being July 2018 in response to U.S. reinstating oil sanctions against the nation. The U.S. Energy Information Administration (2018) lists the Strait of Hormuz as the worlds most important chokepoint, given that it sees roughly 30% of all maritime-traded crude oil and other liquids. In 2016 the strait enjoyed a record high oil flow of 18.5 million barrels per day. Furthermore, 80% of the oil transported through the strait was destined for Asian markets - specifically China, Japan, South Korea, India, and Singapore (U.S. Energy Information Administration, 2014). Should Iran close the Strait of Hormuz, the Asian countries listed would be left searching for an alternate oil supply chain.

The free unhindered flow of the global oil supply is paramount to the security of a nation. Countries who are major oil exporters command the attention of countries who are major oil importers. What then can be said of the global food supply?

An estimated 55% of globally-traded cereals and soybeans are shipped via maritime means that pass through at least one maritime chokepoint (Bailey and Wellesley, 2017). However, since not all oil exporting countries are food exporting countries, the importance of food chokepoints might differ from existing oil chokepoints, or introduce new chokepoints entirely. For example, according to the United Nations Statistics Division (2019), the United States is the worlds largest maize exporter and second largest soybean exporter, with most of those crops being shipped down the Mississippi River to the Port of New Orleans. From New Orleans, ships loaded with food must exit the Gulf of Mexico to reach the Atlantic. Should the Port of New Orleans experience a direct hit from a hurricane (as it did with Katrina in 2005) or a hostile nation enter the Gulf of Mexico, the world's food supply could be impacted. Unlike oil, chokepoint analysis for the global food supply is scant.

A notable contribution to the study of chokepoints in the global food supply has been by Wellesley et al. (2017). The authors reconciled multiple maritime shipping databases into one single database. This single database was then used to power the Chatham House Maritime Analysis Tool (CH-MAT), an excel-based tool that models global cereals imports and exports. The tool then allowed the authors to identify which chokepoints were most important to certain cereals, and then determine which countries were most at risk to chokepoint disruptions.

Ducruet (2016) modeled global maritime flows as complex networks to measure the vulnerability of global maritime trade flows through the Suez and Panama Canals. The author built the network with links weighted by summing the vessel capacities which passed through established links and nodes in a single year. In the years of the study, the author determined that North America was the most canal-dependent region in the world, as the rise of Asia has increased trade flows to the U.S. East Coast. The author concluded the research stating modeling and simulation could predict the impact of new shipping routes and further disruptions to the global shipping network.

Viljoen and Joubert (2016) also used complex network theory to model global container shipping. Their network modeled routes and ports as links and nodes, respectively. Once built, the authors then systematically removed links and nodes to determine the global maritime network's robustness and flexibility. When the authors removed links in a highly connected core of the network, this greatly impacted transshipment alternatives. And when the common skeleton connecting the network was disrupted, this effected shipping opportunities by reducing the set of shortest paths between nodes.

The previous two approaches to modeling global maritime supply chains both used optimization techniques, minimizing either cost or distance. Once links or nodes were removed, the system would optimize the altered network by sending resources on a different link or to a different node. However, if a supply chain displays variance (demand variance, quality variance, supplier variance, etc.), then methods of optimization are inadequate. Simulation is then the tool of choice (Ingalls, 1998). Furthermore, given the size and complexities of supply chain networks, simulation is considered a valid approach since it can incorporate uncertainties and adverse external events (Deleris and Erhun, 2005).

Discrete-event simulation has been used previously to evaluate a country's food export supply chain. Lopes et al. (2017) constructed a discrete-event simulation to improve the efficiency of Brazil's soybean exports. The authors note that recent studies into the logistics of grain exportation have generally used static or optimization models, where the dynamic nature of food production and transportation is not considered. Given the stochastic nature of discrete-event simulation, the authors chose to use this modeling technique to better describe their food export system (Lopes et al., 2017).

The model created by Lopes et al. (2017) considers both single and multi-modal routes, given the export of Brazils soybeans uses roadways, internal waterways, rail, and ocean transport. The model chooses from pre-existing routes to get the soybeans to market in the most cost-effective way. Once the soybeans reach a Brazilian ocean port, the soybeans are then shipped via maritime transport to Brazil's principal soybean importers - Shanghai, China and Hamburg, Germany. Once these soybeans are loaded on a ship, the model uses a triangular distribution to determine the ships speed. Other than ship speed, no other stochastic elements are introduced to the maritime shipping route.

2.3 Model Development

This research develops a simulation model of a subset of world-wide maritime food distribution with a focus on chokepoint disruption. The model was built in Simio and follows the transport methodology of Woxenius (2007). Ships are modeled as entities and carry a 55,000 Dry Weight Tonnage (Handymax/Supramax class). The ships move from node to node in what Simio calls "FreeSpace," with node movements determined by a node list. In FreeSpace movement, entities simply move in the direction of the next node and do not require a link or path. This allows the entities to be easily rerouted should rerouting be necessary. Transshipment activities are not modeled, as ships are considered dry-bulk and route directly to the importer.

At the start of the simulation, a monthly amount of a commodity (measured in metric tons) is divided among ships, where the model creates as many ships as needed to carry that month's shipment. All ships for that month are created at the beginning of the month and placed in a delay, where the delay results in an evenly-spaced division of ships within the specific month. To measure distance, Simio has recently added the ArcGIS World Imagery functionality, incorporating a hi-resolution scale satellite map on the background. This functionality also permits placing model objects using lat/long coordinates (way-points), which allows for accurate distance measurements.

Given their ubiquity in global diets, the commodities of wheat, maize, and soybeans were chosen for this disruption analysis. The importing countries of China, Japan, Egypt, and Spain were selected due to their large import reliance of at least one of the commodities under study. Exporting countries were then selected by evaluating common exporters between the selected importers. Six common exporters were selected - the United States, Brazil, Canada, Argentina, Ukraine, and Russia. Using just these six exporters provided a high percentage of an importer's annual supply of a commodity. For example, these six exporting countries supplied over 98% of Japan's soybean imports in 2017 (United Nations Statistics Division, 2019). Rice was subsequently not considered, as additional exporting countries would be needed. The addition of rice exporters could be the focus of future research. Additional coverage proportions are provided in Figure 7.

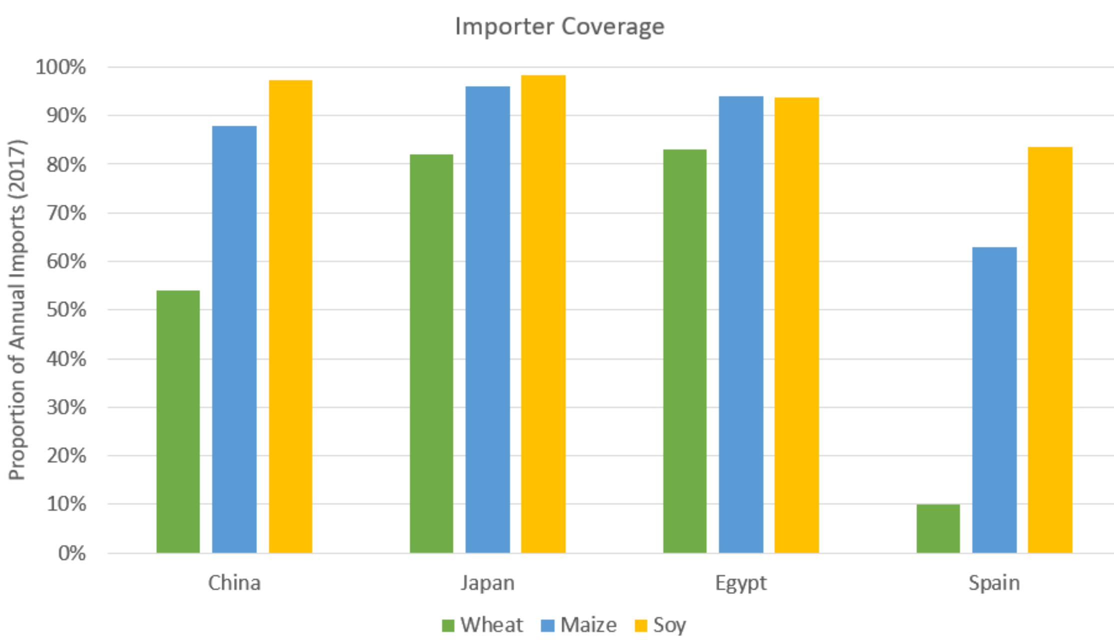

Figure 7. Annual Imports in 2017. Data source: United Nations Statistics Division (2019)

In order to approximate maritime route distances, the ArcGIS background map provided by Simio was used. Starting nodes were placed representing each exporting country's primary export location. Russia and Ukraine have their starting nodes in the Black Sea, and Argentina's near Buenos Aries. The remaining exporters have two export locations each: The United States and Canada have an export location on both east and west coasts, and Brazil north and south. Given that the data does not differentiate which coast/port a commodity originated, a percentage is used to split the monthly commodity amount to a country's respective coast. Once the commodity is split and a ship created, the model evaluates any chokepoint closures and subsequently routes ships to their destinations. Initial travel distances are known and are used to assign the shortest path to each of the four destinations. Travel speed is stochastic and is modeled via a triangular distribution, with maximum and minimum values within 10% of the mean of 14 mph. Monthly commodity export data is provided by the United Nations Statistics Division (2019), and is also stochastic via a triangular distribution with maximum and minimum values within 10% of the United Nations' reported monthly value.

During initial ship routing, if the primary route is not clear (for example, a chokepoint is closed), the ship evaluates a list of alternate routes and chooses the next shortest option. This alternate route list contains initial distances measured from the ship's point of origin to a destination, so selecting the shortest path is somewhat trivial. However, if the ship is already underway and a chokepoint is then closed, these initial distances are no longer valid since the ship is no longer at its origin. For example, if a ship originating from the Gulf of Mexico is underway to Japan and the Panama Canal closes, this ship would have three alternate routes to choose from: Japan via Strait of Gibraltar, Cape of Good Hope, or Cape Horn. The Northwest Passage would also be viable, but northern routes are not considered in this research. There are many factors that could influence a ship captain's decision, but for purposes of this research the route with the smallest distance is chosen. Given these distances change with every movement of the ship, a dynamic route-measuring ability was needed.

Using the above example, a ship underway on a route that would eventually utilize the Panama Canal would have to instantaneously evaluate the remaining three options. Therefore at chokepoint closure, the simulation identifies any ship currently on route to the Panama Canal and begins the rerouting process. In this process, a ship evaluates options by creating clones of itself that travel all remaining possible routes nearly instantaneously. Whichever of these clones reaches the destination first reports the fastest route back to the originating ship, which is then rerouted to that specific route. This allows for easy and fast rerouting once a chokepoint closes.

The same process is used when a chokepoint is reopened. Again, if the Panama Canal is reopened after a closure, the simulation identifies all ships that originally intended to use the Panama Canal and begins the rerouting process once again. However, when a chokepoint reopens, an additional clone is made to travel the route the ship is currently on, as the ship might be too far into its alternate route to consider utilizing the newly opened chokepoint. Again, this allows the ship to evaluate all route options dynamically.

2.4 Supporting Data

Commodities data used in this model are sourced from the United Nations International Trade Statistics Database (known as UN COMTRADE). This database houses some three billion records from over 170 reporting countries, with records dating back to 1962. This data is also available in both monthly and annual timeframes, and is available publicly (United Nations Statistics Division, 2019).

Monthly exports of wheat, maize, and soybeans are imported from UN COMTRADE and are subsequently used to determine demand. Monthly data are used versus annual due to the fact the commodities under study are seasonal - the amount of grain a country exports depends on the harvest season/month. Using monthly data provides insight not only into which chokepoints are most critical for the shipment of these foodstuffs, but also which month is most critical as well.

2.5 Verification and Validation

Initially, the model was intended to be verified using monthly commodity imports into each importing country. For example, if the United States shipped 100% of a country's wheat in a month and travel time was 30 days, we would expect to see that same amount a month later on that importers balance sheet. However, this was not the case. While it is true most foodstuffs are shipped over water, not all are dry-bulk. An increasing number of food shipments are being containerized, a process that allows decreased shipping costs as these containers can ship with other containers. This means containers could spend several months in storage before shipping. Therefore, comparing simulated travel distances to known travel distances is used as a validation measure.

The MarineTraffic (2019) database is used to validate model route distances. MarineTraffic is a leader in ship tracking, using historical Automatic Identification System (AIS) data to provide accurate estimates of ship movements. The AIS is a vessel tracking system that utilizes a ship's on-board transponder to track its whereabouts. Using MarineTraffic's Voyage Planner, the distance of 37 unique simulated routes are compared to their matching real-world routes. Of the 348,154 cumulative miles the 37 routes cover, the model is within 0.0012%, or 4.17 miles.

2.6 Results and Analysis

The country of China is considered for the disruption analysis, with the maritime chokepoints of the Panama Canal, the Suez Canal, and the Strait of Gibraltar being closed to all ship traffic during the months of January and July of 2017. Chokepoints are closed for lengths of 30 and 60 days, then reopened. Although the model is capable of analyzing any commodity, soybeans are the only commodity considered in this analysis.

Four separate scenarios are analyzed: a baseline scenario with all chokepoints open, and three additional scenarios each with a single chokepoint being closed. Scenarios have 30 replications each, and statistical significance is determined at the 0.05 alpha level. Measurements are taken each month and are not cumulative over months. Each value indicates how much of a commodity was received in that month alone.

Chokepoint closures of 30 and 60 days in January 2017 revealed a statistically significant dependency of Chinese soybean imports through the Panama Canal. However, this shortage is not immediately felt. Considering a 30-day closure, the impact of a closure event in January is not seen until the following month of February, as Figure 8 suggests.

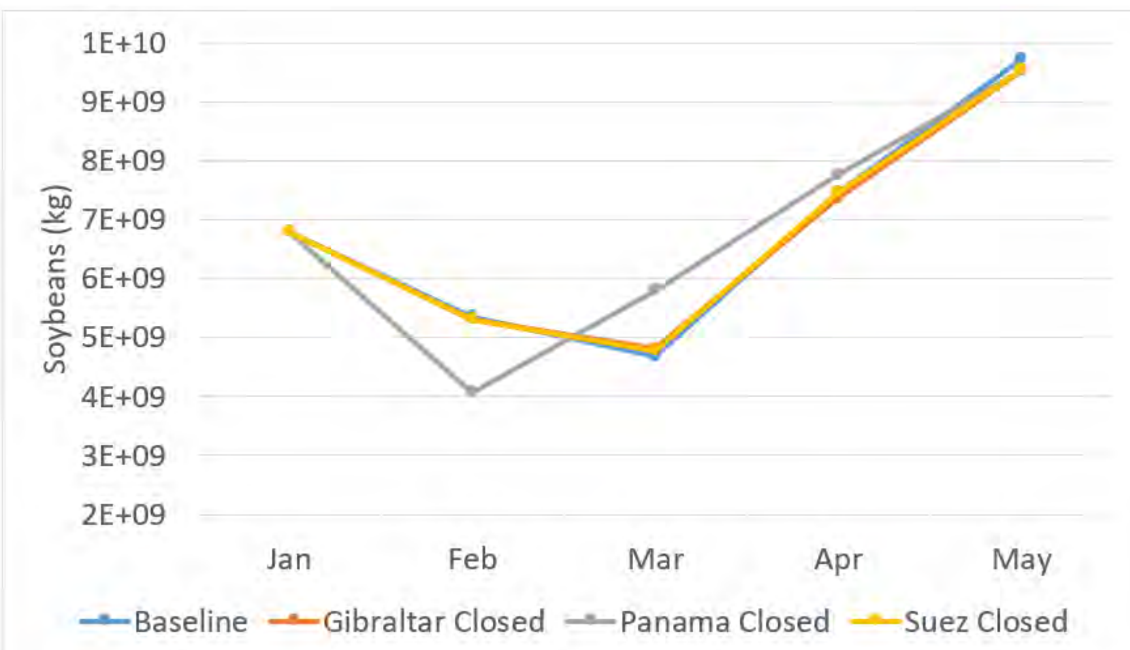

Figure 8. Chinese Soybean Deliveries w/ 30-day Closure in Jan 2017

Compared to the baseline case, a 30-day closure of the Panama Canal in January caused a 31% decrease of average soybeans received in February. Subsequently, the month of March experienced a 28% increase in average soybeans received as compared to the baseline. This is likely due to the displaced ships finally arriving, and the fact that the chokepoint reopened in February. No statistical relationship impacting Chinese soybean imports was detected for closures of either the Suez Canal or Strait of Gibraltar in the month January.

Figures 9 and 10 contain the same data as Figure 8, but also contain the 95% confidence intervals around the mean. Figure 9 displays soybean imports to China for the month of February 2017 - one month after a January 2017 closure of a chokepoint.

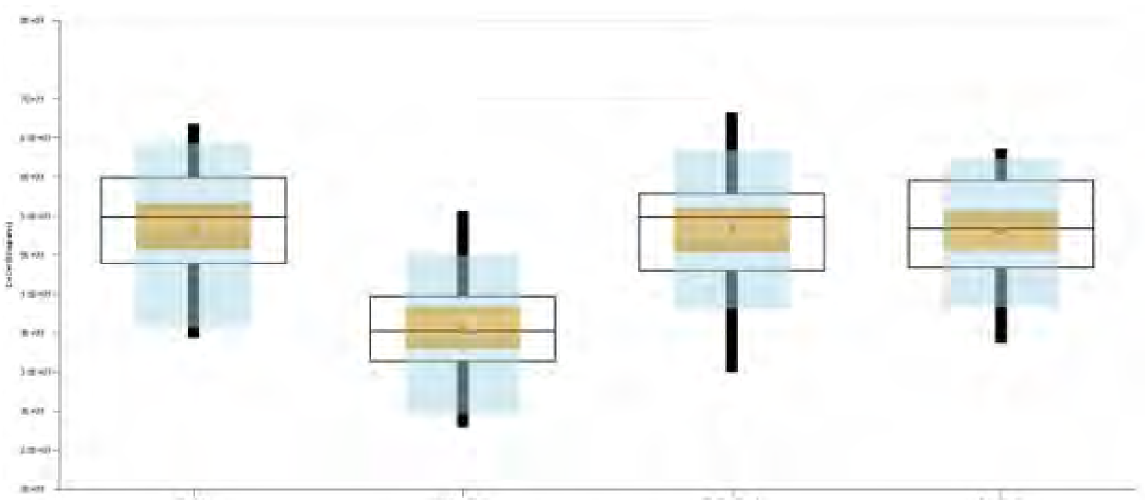

Figure 9. Chinese Soybeans (kg) - February Imports After January Closure (2017)

The month of March (Figure 10) sees the eventual increase of soybean imports to China, as the rerouted ships finally arrive. The shortage caused by rerouting in one month and subsequent late arrivals in the next are both statistically significant at the alpha level of 0.05.

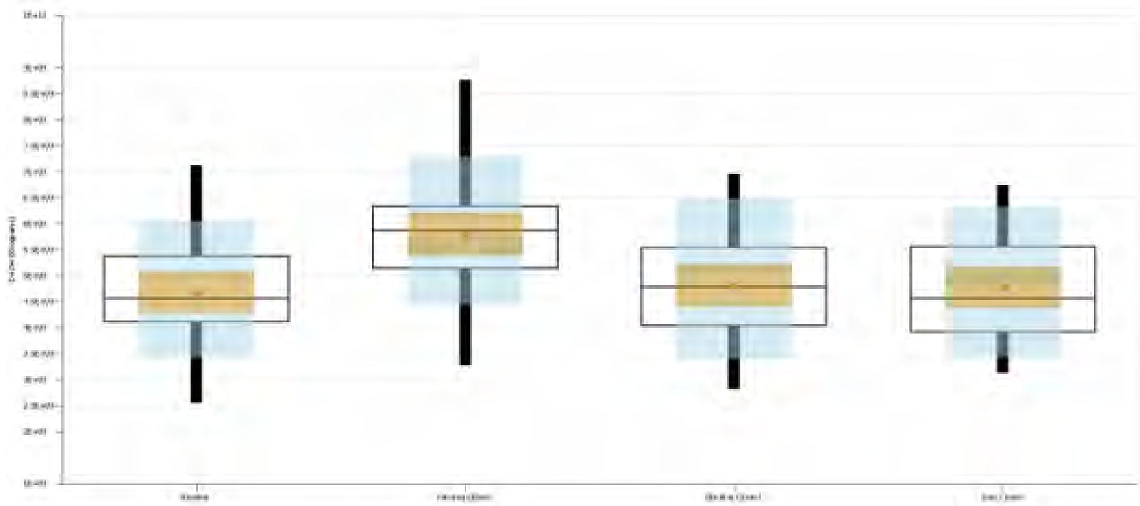

Figure 10. Chinese Soybeans (kg) - March Imports After January Closure (2017)

Considering a closure of 60 days revealed results similar to a closure of 30 days, as the same average soybean decrease was seen in February. However, due to the extended length of the closure, the excess soybeans did not arrive until two months later in April, as Figure 11 details.

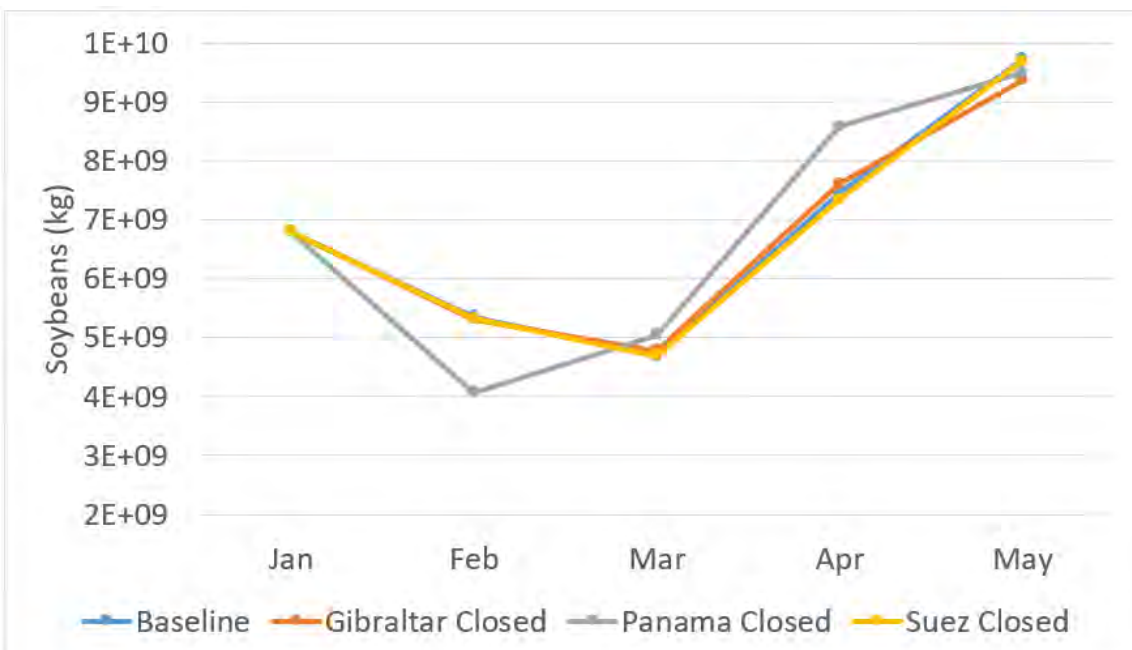

Figure 11. Chinese Soybean Deliveries w/ 60-day Closures

Closures during the month of July indicated no significant relationship as compared to the baseline, despite more soybeans being delivered. This is most likely related to where China sources its soybean imports. In 2017, China received 53% of its soybeans from Brazil and 35% from the United States (United Nations Statistics Division, 2019). As most Brazilian soybeans are exported from the country's southern ports, ships destined for China prefer southern maritime routes which bypass the Panama Canal completely due to the shorter distance. Additionally, while some Brazilian soybeans are exported from the country's northern ports and subsequently traverse the Panama Canal, the amount disrupted is not enough to significantly have an overall impact.

Given the seasonal nature of agriculture, an excursion was explored to determine if there exists a seasonal trend of when China is most sensitive to a chokepoint disruption. Chinese soybean imports are still considered, but only the Panama Canal was tested with closure lengths of 30 days. Two years of trade data are used (2016 & 2017), and only one closure can occur in each month, for a total of 24 unique scenarios. Table 1 contains the soybean shortage results.

Table 1. Chinese soybean shortage w/ 30-Day Panama Canal closure

Disruption	Shortage	2016	2017
Jan	Feb	**-28.7%**	**-24.3%**
Feb	Mar	**-20.6%**	0%
Mar	Apr	**-14.1%**	0%
Apr	May	0%	0%
May	Jun	0%	0%
Jun	Jul	0%	0%
Jul	Aug	0%	0%
Aug	Sep	0%	0%
Sep	Oct	**-11.6%**	**-11.9%**
Oct	Nov	**-31.3%**	**-23.1%**
Nov	Dec	**-27.3%**	**-25.4%**
Dec	Jan	**-26.5%**	**-21.6%**

According to Table 1, China is most sensitive to a Panama Canal closure during the end of the year or at the beginning of the next. Again, this can be traced to the soybean harvest season in the United States, which is during this time-frame (see Figure 12).

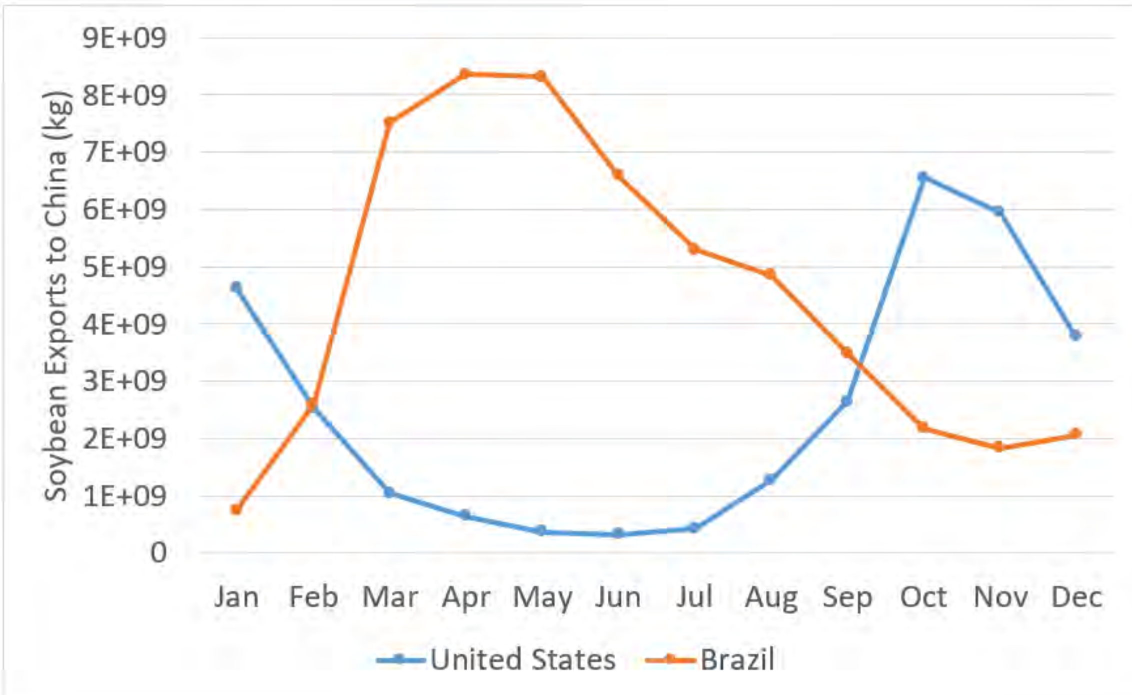

Figure 12. U.S. and Brazilian Soybean Exports to China in 2017. Data source: United Nations Statistics Division (2019)

However, China is not only sensitive to a closure of the Panama Canal. A closure of the Suez Canal can also have a negative impact on shipments to China. Table 2 contains monthly ship arrivals to China, and is for all modeled commodities.

Ship arrivals can be linked directly to shortages, as the significant months in the "Panama Canal" column of Table 2 match the significant months of the "2017" column in Table 1. Both columns are measurements from the same year. Chapter 3 dives further into the relationship between the Suez Canal and China.

Table 2. Chinese ship arrivals w/ 30-Day closures (2017)

Disruption	Gibraltar	Panama Canal	Suez Canal
Jan	0%	**-11.6%**	0%
Feb	0%	0%	**-10.0%**
Mar	0%	0%	0%
Apr	0%	0%	0%
May	0%	0%	**-9.4%**
Jun	0%	0%	0%
Jul	0%	0%	**-8.4%**
Aug	0%	0%	**-8.5%**
Sep	0%	**-7.3%**	0%
Oct	0%	**-14.3%**	**-6.5%**
Nov	0%	**-13.4%**	**-7.9%**
Dec	0%	**-8.7%**	**-7.4%**

2.7 Conclusions

China is a leading importer of global soybeans, and predominately gets those soybeans from both the United States and Brazil (United Nations Statistics Division, 2019). Given most of these soybeans travel via maritime means, this exposes China to chokepoint disruption risk. Should a disruption happen, China could be facing a heavy shortage of a diet staple, which could potentially result in famine if protective measures are not taken.

Given the increasing size of the global economy, the free flow of goods becomes more important each day. Although the event of any one chokepoint closing is extremely rare, the consequences can be painfully high. Historically, the United States (and its Navy) has been the guarantor of global maritime trade, providing countries access to global markets and enabling them to prosper. However, given the increasing global climate of populism and ideas of isolationism coming from the United States recently, maritime trade might not be as safe as historically seen.

III. Case Study

3.1 Introduction

With globalization and the global economy, the world is now more connected than ever. Never has there been an age where nations depended so heavily on other nations for resources (i.e. oil). Merriam-Webster Online (2019) defines a resource as "a natural feature or phenomenon that enhances the quality of human life." Oil certainly makes life easier, but it's only there to "enhance." What then, if not oil, would be a resource that's a *requirement* for human life? One answer is food, which can be captured in a model using a representative set of cereals and soybeans (Jones and Ejeta, 2016; Wellesley et al., 2017).

Maize, rice, and wheat make up almost two-thirds of the world's dietary energy needs (Jones and Ejeta, 2016). Of these three cereals, just six countries provide 70% of the global supply. Furthermore, soybeans account for three-quarters of global livestock feed, and only three countries provide 80% of the global supply (Wellesley et al., 2017). These megacrops are the backbone of the global food supply, and only a handful of countries export them. According to Bailey and Wellesley (2017), 2.8 billion people are fed via food imports from the global transport system each year. Assuming a population of seven billion people in the world, this equates to 40% of the world's population being reliant on global transport to meet their daily caloric needs.

3.2 Background

Given the global requirement for imported food, the free flow of transportation becomes important. A large proportion of the worlds traded cereals and soybeans are shipped via maritime means (Bailey and Wellesley, 2017). Once loaded, these ships follow accepted maritime shipping routes, as shown in Figure 13.

Figure 13. Eurasia Maritime Shipping Routes (Kiln, 2019)

As can be seen in Figure 4, ship traffic concentrates around global maritime chokepoints. A chokepoint is "a strategic narrow route providing passage through or to another region" (Merriam-Webster Online, 2019). In the case of maritime shipping, these chokepoints connect one geographic body of water to another. The disruption of the free flow of global cereals and soybeans through these chokepoints is the focus of this study.

An estimated 55% of globally-traded cereals and soybeans are shipped via maritime means that pass through at least one maritime chokepoint (Bailey and Wellesley, 2017). However, since not all oil exporting countries are food exporting countries, the importance of food chokepoints might differ from existing oil chokepoints, or introduce new chokepoints entirely. Unlike oil, chokepoint analysis for the global food supply is scant.

3.3 Maritime Shipping Simulations

Given the global use of maritime shipping and its importance to economic well–being, the modeling of maritime networks is a frequent endeavor. Ducruet (2016) modeled global maritime flows as complex networks to measure the vulnerability of global maritime trade flows through the Suez and Panama Canals. Viljoen and Joubert (2016) also used complex network theory to model global container shipping, systematically removing links and nodes to determine the global maritime networks robustness and flexibility. These models used optimization techniques, minimizing either cost or distance. However, if a supply chain displays variance (demand variance, quality variance, supplier variance, etc.), then methods of optimization are inadequate and simulation is then the tool of choice (Ingalls, 1998). Furthermore, given the size and complexities of supply chain networks, simulation is considered a valid approach since it can incorporate uncertainties and adverse external events (Deleris and Erhun, 2005).

Specifically, concerning the variation introduced by weather, ship speeds, and varying crop yields, simulation has been the preferred analytic method of choice to capture this variability. Qu and Meng (2012) used a Cellular Automata (CA) simulation model in conjunction with a discrete-event simulation to simulate ship movements through the Singapore Strait. Caris et al. (2011) developed a discrete-event simulation to model alternative transport options for container barges in the port area of Antwerp. The authors analysis was mainly concerned with the impact different hub scenarios had on waiting times and turnaround times for vessels within the port area. Smith et al. (2009) modeled ship congestion in the Upper Mississippi River with a discrete-event simulation, examining ship activities under a wide range of operating conditions.

Concerning global chokepoints, Köse et al. (2003) used a discrete-event simulation to model ship traffic flowing through the Istanbul Strait, and found that an increase of ship arrivals of just 36% causes ship waiting times to jump from a mere 16 minutes to 918 minutes. Mavrakis and Kontinakis (2008) built a similar discrete-event simulation to model maritime traffic through the Strait as well and arrived at similar results. Lopes et al. (2017) constructed a discrete-event simulation to improve the efficiency of Brazil's soybean exports.

A notable contribution to the study of maritime chokepoints in the global food supply has been by Wellesley et al. (2017) and Bailey and Wellesley (2017). The authors reconciled multiple maritime shipping databases into one single database. This single database was then used to power the Chatham House Maritime Analysis Tool (CH-MAT), an excel-based tool that models global cereals imports and exports. The tool then allowed the authors to identify which chokepoints were most important to certain cereals, and then determine which countries were most at risk to chokepoint disruptions. However, no stochastic elements or seasonal trends were considered.

3.4 Model Development

This research develops a simulation model of a subset of world-wide maritime food distribution with a focus on chokepoint disruption. The model was built in Simio and follows the transport methodology set fourth by Woxenius (2007). Ships are modeled as entities and carry a 55,000 Dry Weight Tonnage (Handymax/Supramax class). Each month, metric tonnes of wheat, maize, and soybeans are shipped dry-bolk to their destination. Ships travel directly to their destinations, as transshipping or refuleing is not considered.

Distance is measured using the ArcGIS World Imagery functionality in Simio, incorporating a hi-resolution scale satellite map on the background. This functionality also permits placing model objects using lat/long coordinates (way-points), which allows for accurate distance measurements.

The importing countries of China, Japan, Egypt, and Spain were selected due to their large import reliance of at least one of the commodities under study. Given these four importers, six common exporters are selected - the United States, Brazil, Canada, Argentina, Ukraine, and Russia. Using these six exporters provides a high percentage of an importer's annual supply of a commodity. Travel speed is stochastic and is modeled via a triangular distribution, with maximum and minimum values within 10% of the mean travel speed of 14 mph. Monthly commodities data is also stochastic via a triangular distribution with maximum and minimum values within 10% of the United Nations' reported monthly exported value.

Initial route selection is determined via distances collected from MarineTraffic (2019) and are modeled herein. However, during a chokepoint disruption, a ship will reroute itself using whichever route is shortest in distance. This occurs dynamically, as the ship entity is continuously aware of which alternate route is fastest should a chokepoint close. The same process is used when a chokepoint reopens, as the reopened route might now be shortest.

3.5 Supporting Data, Verification and Validation

Commodities data used in this model are sourced from the United Nations International Trade Statistics Database. This data is available in both monthly and annual timeframes, and is available publicly (United Nations Statistics Division, 2019).

Monthly exports of wheat, maize, and soybeans from United Nations Statistics Division (2019) are used to determine demand. Monthly data are preferred to annual due to the fact the commodities under study are seasonal - the amount of grain a country exports depends on the harvest season/month. Using monthly data provides insight not only into which chokepoints are most critical for the shipment of these foodstuffs, but also which month is most critical as well.

The MarineTraffic (2019) database is used to validate model route distances. MarineTraffic is a leader in ship tracking, using historical Automatic Identification System (AIS) data to provide accurate estimates of ship movements. The AIS is a vessel tracking system that utilizes a ship's on-board transponder to track its whereabouts. Using MarineTraffic's Voyage Planner, the distance of 37 unique simulated routes are compared to their matching real-world routes. Of the 348,154 cumulative miles the 37 routes cover, the model is within 0.0012%, or 4.17 miles.

3.6 Comparison

The countries of China, Japan, Egypt, and Spain are considered for the disruption analysis, with the maritime chokepoints of the Panama Canal, the Suez Canal, and the Strait of Gibraltar being individually closed to all ship traffic. Chokepoints are closed for 30 days, then reopened. Monthly exports of wheat, maize, and soybeans are considered.

Four separate scenarios are analyzed: a baseline scenario with all chokepoints open, and three additional scenarios each with a single chokepoint being closed. Scenarios have 30 replications each, and statistical significance is determined at the 0.05 alpha level.

3.6.1 Panama Canal

Closing the Panama Canal for 30 days revealed a statistically significant decrease in monthly wheat imports to Japan and Egypt, as shown in Table 3.

Table 3. Wheat via Panama Canal: 30-Day closures

Disruption	China	Japan	Egypt	Spain
Jan	0%	**-14.0%**	0%	-
Feb	0%	0%	0%	-
Mar	0%	**-5.2%**	0%	-
Apr	0%	0%	0%	-
May	0%	0%	0%	-
Jun	0%	**-10.4%**	**-3.7%**	-
Jul	0%	**-5.5%**	0%	-
Aug	0%	**-13.2%**	0%	-
Sep	0%	**-8.5%**	0%	-
Oct	0%	**-16.1%**	0%	-
Nov	0%	**-14.8%**	0%	-
Dec	0%	**-9.0%**	0%	-

Japan was most sensitive, experiencing significant decreases in nine of twelve months. Egypt was less dependent, experiencing a significant decrease in only one month. Egypt's resilience in its wheat imports is likely due to it sourcing over 80% of its imported wheat from Russia and Ukraine (United Nations Statistics Division, 2019). Neither country utilizes the Panama Canal to reach Egypt. However, both Russia and Ukraine must use the Turkish Straits for maritime shipping, which is one of the narrowest chokepoints in the world and has no alternate maritime route. The Turkish Straits are not considered in this analysis.

Wheat imports to Spain are under-represented by this research and are therefore omitted (denoted by "-"). Spain sourced only 10% of their 2017 wheat imports from the six exporters in this study (United Nations Statistics Division, 2019).

Maize shipments between the six exporters and our four importers revealed no significant decreases in monthly shipments. According to the United Nations Statistics Division (2019), China, Japan, Egypt, and Spain sourced their 2017 maize imports from countries that either bypass the Panama Canal completely, or use it only for a portion of the total shipment.

Soybean imports, however, were significantly impacted when the Panama Canal closed.

Table 4. Soybeans via Panama Canal: 30-Day closures

Disruption	China	Japan	Egypt	Spain
Jan	**-24.3%**	**-2.8%**	0%	**-5.9%**
Feb	0%	0%	0%	**-6.0%**
Mar	0%	0%	0%	0%
Apr	0%	0%	0%	0%
May	0%	0%	0%	0%
Jun	0%	**-6.7%**	0%	0%
Jul	0%	**-5.1%**	0%	0%
Aug	0%	0%	0%	0%
Sep	**-11.9%**	**-4.4%**	0%	0%
Oct	**-23.1%**	0%	0%	**-9.0%**
Nov	**-25.4%**	**-5.0%**	0%	**-34.3%**
Dec	**-21.6%**	**-8.0%**	0%	**-11.8%**

According to United Nations Statistics Division (2019), China, Japan, and Spain rely heavily on North and South America for their soybean imports. China is most reliant on the United States and Brazil, with both countries supplying 89% of total soybean exports to China in 2017. China's sensitivity from closing the Panama Canal occurs when it is importing soybeans from the United States, which utilizes the Panama Canal to access the Pacific Ocean. Brazil bypasses the Panama Canal, as the southern route utilizing the Cape of Good Hope and the Strait of Malacca is shorter. Japan, however, is most reliant on the United States and Canada for their soybean imports, receiving 84% of total imports from these two exporters in 2017 (United Nations Statistics Division, 2019). Both countries utilize the Panama Canal to reach the Pacific.

Even though Spain is East of the Panama Canal, shipments from the West Coast of the United States and Canada still traverse the Panama Canal to reach Spain. Egypt experienced no significant impact from a Panama Canal closure, as it sourced almost 50% of its 2017 soybean imports from exporters that bypass the Panama Canal.

3.6.2 Strait of Gibraltar

The Strait of Gibraltar connects the Atlantic Ocean with the Mediterranean Sea, and is part of a sea route connecting the West to the East.

Wheat imports were impacted in only two of twelve months for both China and Egypt, as displayed in Table 5.

Table 5. Wheat via Strait of Gibraltar: 30-Day closures

Disruption	China	Japan	Egypt	Spain
Jan	0%	0%	0%	-
Feb	0%	0%	0%	-
Mar	0%	0%	0%	-
Apr	0%	0%	0%	-
May	0%	0%	0%	-
Jun	0%	0%	**-4.6%**	-
Jul	0%	0%	**-2.8%**	-
Aug	0%	0%	0%	-
Sep	0%	0%	0%	-
Oct	**-27.3%**	0%	0%	-
Nov	0%	0%	0%	-
Dec	**-25.0%**	0%	0%	-

The impact to China can be traced back to its wheat imports from Eastern Canada, as these shipments traverse the Strait of Gibraltar. Egypt is also sensitive to a closure here, most likely due to it importing wheat from the United States and Argentina, both of which use the strait as well.

Maize imports given a Strait of Gibraltar closure highlight an Egypt and Spain dependency on maize from western exporters, as detailed in Table 6.

Table 6. Maize via Strait of Gibraltar: 30-Day closures

Disruption	China	Japan	Egypt	Spain
Jan	0%	0%	**-6.0%**	0%
Feb	0%	0%	**-7.7%**	0%
Mar	0%	0%	0%	0%
Apr	0%	0%	**-25.7%**	**-4.9%***
May	0%	0%	0%	**-11.1%***
Jun	0%	0%	**-59.3%**	**-15.4%***
Jul	0%	0%	**-63.6%**	**-49.9%***
Aug	0%	0%	**-59.8%**	**-83.4%**
Sep	0%	0%	**-52.0%**	**-94.1%**
Oct	0%	0%	**-62.8%**	**-83.0%**
Nov	0%	0%	**-67.9%**	**-84.2%***
Dec	0%	0%	**-51.0%**	**-62.5%**

* Multiple months significant. Maximum shown.

Egypt and Spain imported 34% and 27% of their maize, respectively, from Ukraine - an exporter that does not utilize the Strait of Gibraltar to export to these countries. All other maize exporters represented in this research, however, utilize the Strait of Gibraltar and would have to subsequently reroute around the Cape of Good Hope, then traverse Bab-el-Mandeb and the Suez Canal to reach Egypt and Spain, a voyage that would add weeks to any shipment and add additional cargo risk as ships traverse additional chokepoints.

Soybeans are heavily sourced from western countries, and much like maize, this commodity must also utilize the Strait of Gibraltar to reach Egypt and Spain. Table 7 contains the impact a closure of the Strait of Gibraltar has on soybean imports.

Table 7. Soybeans via Straight of Gibraltar: 30-Day closures

Disruption	China	Japan	Egypt	Spain
Jan	0%	0%	**-37.4%**	**-63.7%***
Feb	0%	0%	**-56.3%**	**-83.9%***
Mar	0%	0%	**-56.3%**	**-79.0%***
Apr	0%	0%	**-48.8%**	**-87.2%**
May	0%	0%	**-46.2%**	**-75.2%***
Jun	0%	0%	**-40.0%**	**-97.0%**
Jul	0%	0%	**-58.4%**	**-91.4%**
Aug	0%	0%	**-52.8%**	**-93.8%**
Sep	0%	0%	0%	**-93.5%***
Oct	0%	0%	**-25.4%**	**-90.0%**
Nov	0%	0%	**-49.6%**	**-66.0%**
Dec	0%	0%	**-54.5%**	**-31.7%***

* Multiple months significant. Maximum shown.

According to the United Nations Statistics Division (2019), both Egypt and Spain sourced most of their soybean imports in 2017 from the United States, Brazil, and Argentina - all countries that utilize the Strait of Gibraltar to reach these importers. While both countries would see significant monthly decreases in their soybean imports, Egypt is still better positioned as it received 23% of its 2017 soybean imports from Ukraine and bypassing the Strait of Gibraltar all together.

3.6.3 The Suez Canal

The Suez Canal heads in Egypt and connects the Mediterranean Sea to the Red Sea. Much like the Strait of Gibraltar, the Suez Canal is a link in the chain connecting West to East.

Closing the Suez Canal had a significant impact on Chinese wheat imports (Table 8), with six of twelve months displaying a significant decrease.

Table 8. Wheat via The Suez Canal: 30-Day closures

Disruption	China	Japan	Egypt	Spain
Jan	0%	0%	0%	-
Feb	0%	0%	0%	-
Mar	0%	0%	0%	-
Apr	0%	0%	0%	-
May	**-17.7%**	0%	0%	-
Jun	0%	0%	0%	-
Jul	**-20.0%**	0%	0%	-
Aug	**-24.5%**	0%	0%	-
Sep	0%	0%	0%	-
Oct	**-34.3%**	0%	0%	-
Nov	**-28.3%**	0%	0%	-
Dec	**-58.9%**	0%	0%	-

China sourced 15% of its 2017 wheat imports from Canada, and when exported from Canada's East Coast these exports traverse the Suez Canal. Closing the Suez Canal forces ships to turnaround and exit the Mediterranean through the Strait of Gibraltar, adding up to a week of additional travel time.

Chinese maize imports appear to be impacted if the Suez Canal closes, as depicted in Table 9.

Table 9. Maize via The Suez Canal: 30-Day closures

Disruption	China	Japan	Egypt	Spain
Jan	0%	0%	0%	0%
Feb	0%	0%	0%	0%
Mar	**-73.7%**	0%	0%	0%
Apr	**-35.5%**	0%	0%	0%
May	**-29.6%**	0%	0%	0%
Jun	0%	0%	0%	0%
Jul	0%	0%	0%	0%
Aug	0%	0%	0%	0%
Sep	0%	0%	0%	0%
Oct	**-27.3%**	0%	0%	0%
Nov	0%	0%	0%	0%
Dec	**-25.0%**	0%	0%	0%

According to the United Nations Statistics Division (2019), Ukraine supplied China with over 61% of its maize imports in 2017, and utilizes the Suez Canal to ship east to China. China also sourced 27% of its 2017 maize imports from the United States - an exporter that bypasses the Suez Canal in favor of the Panama Canal when shipping to China. This provides China a buffer should the Suez Canal close.

Soybean shipments with the Suez Canal closed resulted in no significant decreases in the four importing countries studied. This is likely due to where these four importers reside geographically, and the exporters chosen to study. Soybeans exported to China and Japan utilize the Panama Canal, and those exported to Egypt and Spain utilize the Panama Canal, the Strait of Gibraltar, and the Turkish Straits (those exported from Ukraine).

3.6.4 Impact of Closures on the Strait of Malacca

According to the U.S. Energy Information Administration (2014), the Strait of Malacca is one of the world's most important strategic chokepoints by volume of oil transit, connecting the Indian Ocean to the Pacific Ocean. In 2016, oil flows through here rose to 16 million barrels per day, and is considered the second busiest transit chokepoint behind the Strait of Hormuz. Oil shipments through the Strait of Malacca supply the growing economies of China and Indonesia.

Given the Strait of Malacca's importance in global trade, the free flow of ship traffic becomes paramount. However, this free flow could be jeopardized with the closure of a chokepoint half a world away.

When a chokepoint closes, ships will reroute to their destination using the shortest route available. If a ship is destined for China and the Panama Canal closes, the shortest route often available is one utilizing the Strait of Malacca. Should an entire fleet of exports need to reroute to traverse the Strait of Malacca and not be able to pass due to increased arrivals, the free flow of ship traffic is no longer viable and the system could come to an abrupt halt.

The following analysis is a measure of monthly arrivals to the Strait of Malacca given a chokepoint closure of 30 days. Arrival values are listed for each month (using 2017 data) as percentage increase or decreases from the baseline case of no closures. Each figure is a representation of what the Strait of Malacca could expect if a chokepoint closed.

Figure 14 depicts monthly expected arrival increases to the Strait of Malacca should the Panama Canal close for 30 days during the listed month. Given the large distance between the Panama Canal and the Strait of Malacca, listed arrival increases are offset by two months. For example, if the Panama Canal closed in January, the listed increase of 80% occurs two months later in March. The figure lists the 80% in January because that is when the chokepoint initially closed.

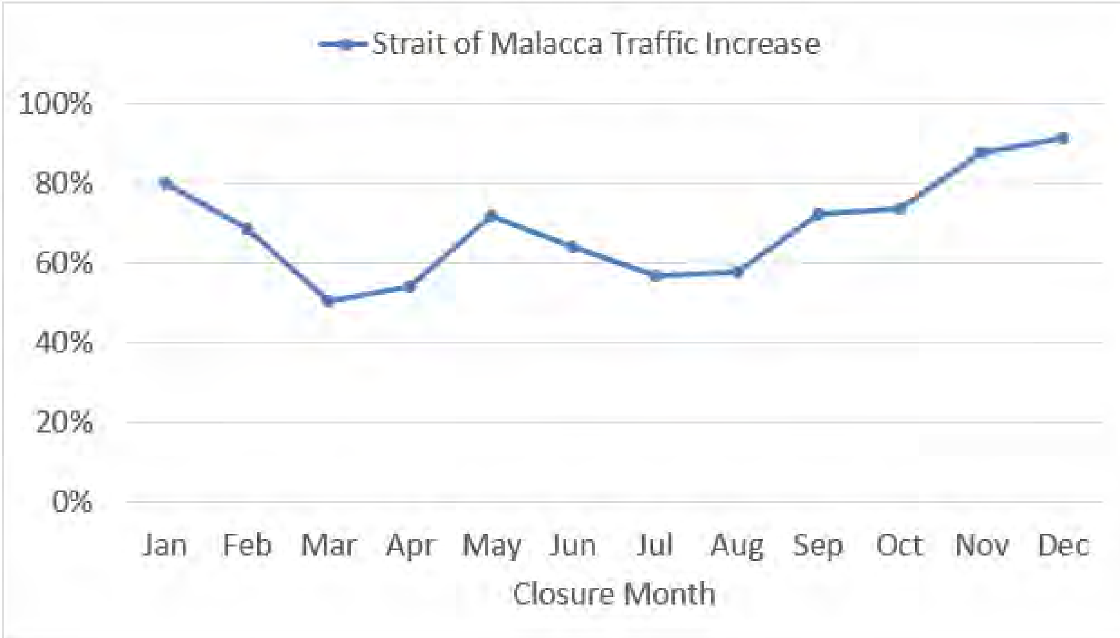

Figure 14. Strait of Malacca Traffic w/ 30-Day Panama Canal Closure

According to Figure 14, should the Panama Canal close, the Strait of Malacca could expect at least a 51% increase in the exports studied in all months, as compared to the baseline, with a maximum increase of nearly double if the Panama Canal closed in the month of December.

Should the Strait of Gibraltar close, smaller increases could be expected, as shown in Figure 15. Unlike Figure 14, the data listed in Figure 15 is offset by only one month, as the Strait of Gibraltar is closer.

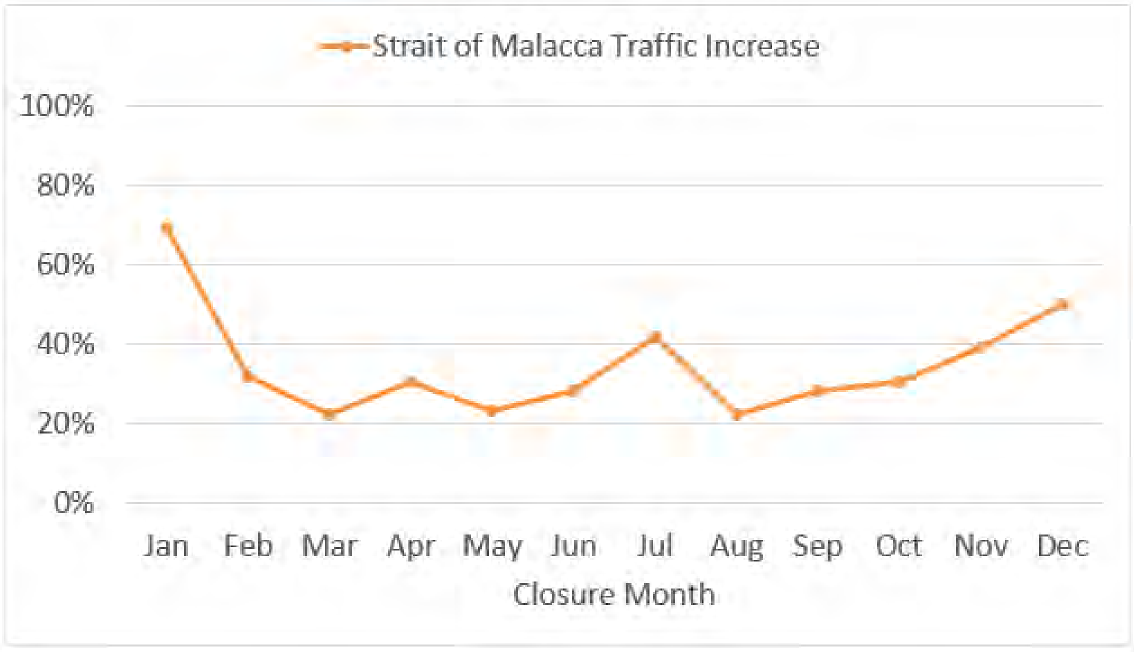

Figure 15. Strait of Malacca Traffic w/ 30-Day Strait of Gibraltar Closure

Traffic increases of at least 20% could be expected, with the largest impact coming from a closure of the Strait of Gibraltar in January. This is likely due to exports emanating from the western United States and Canada to Egypt and Spain, as the primary route is to utilize the Panama Canal then the Strait of Gibraltar. The alternate route for these exporters is to then utilize the Strait of Malacca.

A closure of the Suez Canal (Figure 16), however, results in traffic decreases in the Strait of Malacca. The data in Figure 16 is comparable to Figure 15, with arrival percentages being experienced one month after the listed closure.

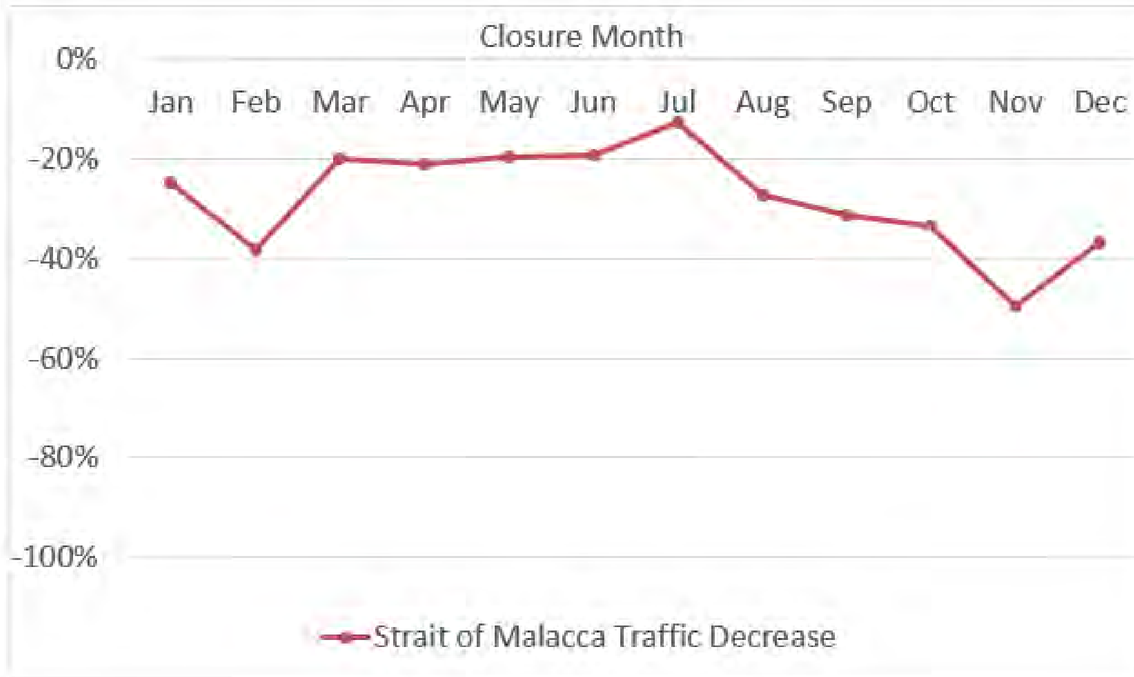

Figure 16. Strait of Malacca Traffic w/ 30-Day Suez Canal Closure

These decreases are likely attributed to ship traffic originating in Russia, Ukraine, and Eastern Canada with a destination of Japan. These exporters utilize the Suez Canal and eventually the Strait of Malacca to export to Japan. Should the Suez Canal close, these exporters would traverse the Panama Canal to reach Japan, completely bypassing the Strait of Malacca.

3.7 Conclusions

North and South America are top exporters of the global food supply. Given most of this food supply travels via maritime means, this exposes any importing country to substantial chokepoint disruption risk. Should a disruption happen, importers could be facing heavy shortages of diet staples, which could potentially result in famine if protective measures are not taken. Shipping costs could skyrocket, as shipping companies are accumulating more distance to reroute around a closure. A shipping cost increase would likely be passed on to the consumer, which could cause the market for these commodities to also skyrocket.

Should the Strait of Malacca experience the increased traffic as detailed in this analysis, oil tankers traversing there will be slowed if not stopped. If oil tankers, or any valuable commodity be slowed or stopped in the Strait of Malacca, cargo safety will be a concern as the waters there have a history of piracy (Hassan and Hasan, 2017).

Given the increasing size of the global economy, the free flow of goods becomes more important each day. Although the event of any one chokepoint closing is extremely rare, the consequences can be painfully high.

IV. Conclusions

4.1 Research Summary

The maritime transport system is the backbone of the global food supply, and arguably the global economy. As the world's population grows, an ever-increasing amount of ships will traverse these maritime chokepoints on their way to countries who's well-being depends completely on their safe and expeditious arrival. The more reliant a country becomes on the maritime transport system, the larger amount of risk they accept.

Considering over half of the world's exported supply of wheat, rice, maize, and soybeans are exported via maritime means, the free flow of marine traffic becomes paramount. Current models lack the ability to capture the inherent variance displayed in the maritime transport system, which can lead to inaccurate assumptions about how the system functions - assumptions that could ultimately bring chaos to an importing economy.

To capture this inherent variance, a discrete-event simulation was built in order to better understand how disruptions in this system impact those who rely on its unhindered functionality. This simulation models ships as entities, with carrying capacities near those of the Handymax/Supramax class. Ships originate in port at an exporting location, then travel along accepted maritime routes to the importer. The commodities of wheat, maize, and soybeans are studied, using monthly export data from the United Nations Statistics Division (2019) to increase granularity and thus provide better estimates of how the system functions on a monthly basis. Rice was not considered, as its primary exporters were not explicitly modeled. The maritime chokepoints of the Panama Canal, the Suez Canal, and the Strait of Gibraltar were modeled for disruption. Chokepoints are closed to all ship traffic for lengths of 30 and 60 days, then reopened.

Results indicate significant food shortages as compared to the baseline for all importers studied, with some receiving 97% less of a commodity as compared to the same month in the baseline case. Chinese imports of soybeans are particularly sensitive to a closure of the Panama Canal in the months of September - January. Egypt and Spain could expect significant decreases of maize and soybeans if the Strait of Gibraltar was closed in any month, with Spain experiencing its worst declines should a disruption occur in September.

Marine traffic through the Strait of Malacca was significantly impacted when one of the three chokepoints studied were closed. Specifically, the Strait of Malacca experienced increases of at least 51% when the Panama Canal closed in any month, with the largest increase of 91% expected if the Panama Canal were to close in December.

4.2 Future Work

Chokepoint capacity should be modeled, as this research assumed an infinite amount of ships could pass through a chokepoint each day. However, this is clearly not the case. Each global chokepoint has an assumed maximum throughput of ships it can handle per day, and capturing this metric could illuminate further how disruptions impact global trade.

Given the Strait of Malacca's importance to global trade, modeling this chokepoint for disruption could reveal more dependencies in the maritime transportation system. Additionally, the Strait of Malacca has two alternate routes within close proximity - the Sunda Strait between the islands of Java and Sumatra, and the Lombok Strait between the islands of Bali and Lombok. Both straits are capable of providing traffic relief should the Strait of Malacca be overwhelmed. Should all three straits experience a disruption (i.e. a blockade), the impact could have global consequences.

Additional countries and specific ports could be modeled, adding more insight into the system. Furthermore, as the simulation is already designed to import/export an unlimited amount of resources, additional commodities should be added to better define importer/exporter relationships. Commodities such as oil and raw materials could illuminate additional maritime dependencies.

Considering the transport system for the global food supply is multi-modal, the addition of rail networks to the simulation would add additional understanding, as alternate routes might include a leg of rail shipments. Moreover, an analysis such as this but specifically for oil transportation could prove fruitful, as the oil transportation system is multi-model as well. For example, should the Strait of Hormuz close, only Saudi Arabia and the United Arab Emirates have oil pipelines that can circumvent the chokepoint. However, they are at far lesser throughput (U.S. Energy Information Administration, 2014).

To better model real-world decision making, additional maritime routes should be added. Specifically, as the earth's temperature increases, routes along the Northwest Passage become viable, and are often of shorter distance than southern routes. However, with the addition of the Northwest Passage comes the potentiality of a new set of global chokepoints. Further analysis should assume these northern routes will eventually fully open and might become the new global standard, bringing the economies of the world closer together.

Appendix A. Simio Model Screenshots

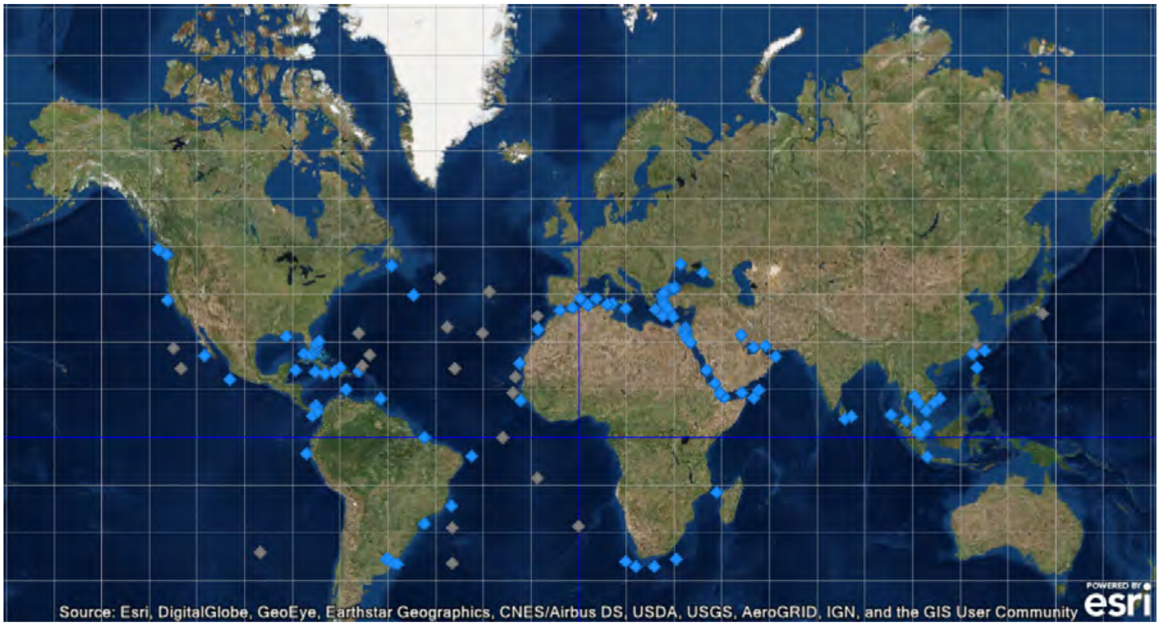

Figure 17. Model overview

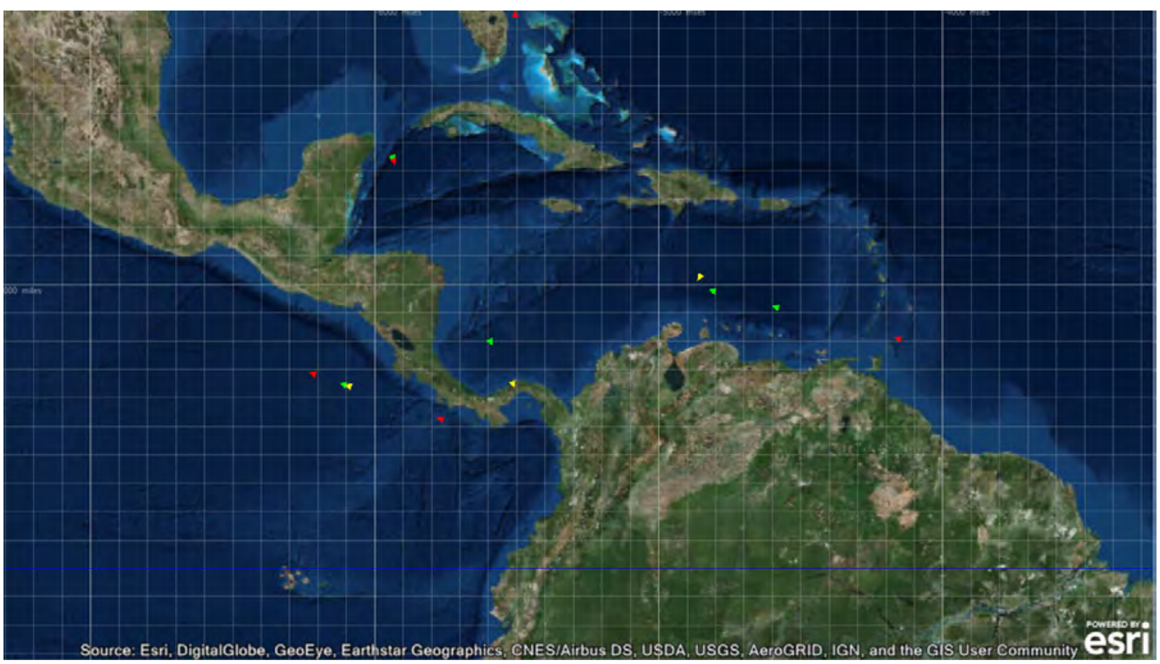

Figure 18. Panama Canal traffic

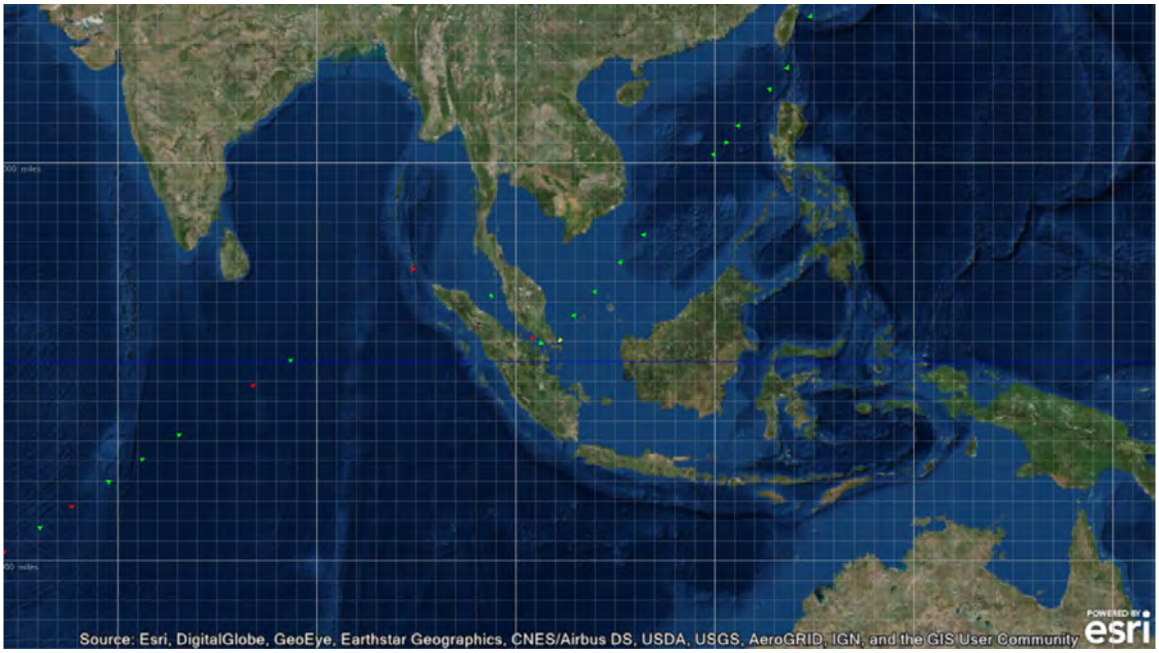

Figure 19. Strait of Malacca traffic

	Origin ID	Importer ID	Priority	First Hub	Second Hub	Third Hub	Fourth Hub	Fifth Hub	Sixth Hub	Seventh Hub	InitialDistance ...
1	22	1	1	12	6	7	9	23	0	0	10204.41506
2	22	1	2	12	4	5	9	23	0	0	19171.90274
3	22	1	3	12	4	10	23	0	0	0	20113.11419
4	22	1	4	12	4	13	23	0	0	0	26769.14516
5	22	2	1	12	6	7	9	24	0	0	11365.93184
6	22	2	2	12	4	10	24	0	0	0	18996.92664
7	22	2	3	12	4	5	9	24	0	0	20333.43102
8	22	2	4	12	4	13	24	0	0	0	25652.55483
9	22	3	1	12	27	0	0	0	0	0	1611.590472
10	22	3	2	12	27	0	0	0	0	0	1611.590472
11	22	3	3	12	27	0	0	0	0	0	1611.590472
12	22	3	4	12	27	0	0	0	0	0	1611.590472
13	22	4	1	12	26	0	0	0	0	0	2843.338178
14	22	4	2	12	26	0	0	0	0	0	2843.338178

Figure 20. Route list (includes all hubs to traverse)

Figure 20 details how an exporter can get to an importer, with corresponding priorities. If a ship is on a certain route and a chokepoint closes, the model searches for ships that are on routes that contain this chokepoint (row search). If it does, the model places this ship on a route that is clear.

	Step1	Step2	Step3	Step4	Step5	Step6	Step7	Step8	Step9	Step10	Step11	Step12	Step13
▸ 1	N8	N9	TP3	N10	N11	N12	COGHN5	ErrN	ErrN	ErrN	ErrN	ErrN	ErrN
2	N8	N9	TP3	N10	N11	N12	COGHN5	ErrN	ErrN	ErrN	ErrN	ErrN	ErrN
3	N52	N114	N115	N25	N26	N18	SuezN6	ErrN	ErrN	ErrN	ErrN	ErrN	ErrN
4	TP2	N42	N13	PanamaN10	ErrN	ErrN	ErrN	ErrN	ErrN	ErrN	ErrN	ErrN	ErrN
5	TP2	N42	N13	PanamaN10	ErrN	ErrN	ErrN	ErrN	ErrN	ErrN	ErrN	ErrN	ErrN
6	N8	N9	TP3	TP10	N40	N41	N43	CHN13	ErrN	ErrN	ErrN	ErrN	ErrN
7	N8	N9	TP3	N40	N41	N43	CHN13	ErrN	ErrN	ErrN	ErrN	ErrN	ErrN
8	N43	CHN13	ErrN	ErrN	ErrN	ErrN	ErrN	ErrN	ErrN	ErrN	ErrN	ErrN	ErrN
9	N8	N9	TP3	TP10	N40	N41	N43	CHN13	ErrN	ErrN	ErrN	ErrN	ErrN
10	N52	N53	Input@SpainSink	ErrN	ErrN	ErrN	ErrN	ErrN	ErrN	ErrN	ErrN	ErrN	ErrN
11	N52	N114	N115	N25	N26	Input...	ErrN	ErrN	ErrN	ErrN	ErrN	ErrN	ErrN
12	N12	N11	N10	N9	N8	Gibral...	ErrN	ErrN	ErrN	ErrN	ErrN	ErrN	ErrN
13	N12	N11	N10	N9	N8	Gibral...	ErrN	ErrN	ErrN	ErrN	ErrN	ErrN	ErrN
14	N14	N15	N36	N38	N20	BabEl...	ErrN	ErrN	ErrN	ErrN	ErrN	ErrN	ErrN

Figure 21. Hub-to-hub routes (node list)

Figure 21 details how ships move from hub to hub (Simio node list). The "ErrN" node is an error node, which stops the simulation should a ship reach it. This was used for debugging.

	Commodity Type	Commodity ID	Period	NetWeightShipped (Kilograms)	Exporter ID	Importer ID
740	Maize	2	201710	6081080	5	1
741	Maize	2	201710	82036360	5	4
742	Maize	2	201710	118810280	5	3
743	Maize	2	201710	3943881	1	1
744	Maize	2	201710	141596081	1	2
745	Maize	2	201710	391554	1	4
746	Maize	2	201710	366463	1	3
747	Maize	2	201710	12000	6	2
748	Maize	2	201710	359100	6	1
749	Maize	2	201711	41550	4	2
750	Maize	2	201711	15317600	4	4
751	Maize	2	201711	197488000	4	3
752	Maize	2	201711	536485040	3	2
753	Maize	2	201711	242632642	3	4
754	Maize	2	201711	256903990	3	3

Figure 22. Monthly export schedule

Figure 22 displays how the model creates commodity shipments. Given a certain month and year, the model will search this table finding entries that match. This allows for an unlimited amount of commodities can be added, so long as they have values in each column (Commodity ID must be unique).

Appendix B. Input Data

Period Desc.	Trade Flow	Reporter	Partner	Commodity	Netweight (kg)
Jan-17	Exports	Argentina	Spain	Maize (corn)	138100
Jan-17	Exports	Argentina	Egypt	Maize (corn)	151430
Jan-17	Exports	Brazil	Egypt	Maize (corn)	199950
Jan-17	Exports	Canada	Japan	Maize (corn)	931304
Jan-17	Exports	Ukraine	Egypt	Maize (corn)	337216313
Jan-17	Exports	Ukraine	Spain	Maize (corn)	453069735
Jan-17	Exports	Ukraine	China	Maize (corn)	85500010
Jan-17	Exports	Ukraine	Japan	Maize (corn)	1244830
Jan-17	Exports	United States of America	Spain	Maize (corn)	573445
Feb-17	Exports	Argentina	Spain	Maize (corn)	216320
Feb-17	Exports	Argentina	Egypt	Maize (corn)	1508000
Feb-17	Exports	Brazil	Egypt	Maize (corn)	22961000
Feb-17	Exports	Ukraine	Spain	Maize (corn)	207884147
Feb-17	Exports	Ukraine	Egypt	Maize (corn)	194816697
Feb-17	Exports	United States of America	Egypt	Maize (corn)	182400
Mar-17	Exports	Argentina	China	Maize (corn)	181
Mar-17	Exports	Argentina	Spain	Maize (corn)	321000
Mar-17	Exports	Argentina	Egypt	Maize (corn)	91796000
Mar-17	Exports	Ukraine	Japan	Maize (corn)	57478110

Figure 23. Example of monthly data download (United Nations Statistics Division, 2019)

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14. ABSTRACT
Considering over half of the world's exported supply of these four commodities are exported via maritime means, the free flow of marine traffic becomes paramount. Current models lack the ability to capture the inherent variance displayed in the maritime transport system, which can lead to inaccurate assumptions about how the system functions - assumptions that could ultimately bring chaos to an importing economy. To capture this inherent variance, a discrete-event simulation was built to better understand how disruptions in this system impact those who rely on its unhindered functionality. Monthly export data is used, and the maritime chokepoints of the Panama Canal, the Suez Canal, and the Strait of Gibraltar are modeled for disruption. Results indicate significant food shortages for all importers studied, with some receiving 97% less of a commodity in a given month. China is particularly sensitive to a closure of the Panama Canal in the months of September - January. Egypt and Spain could expect significant food decreases if the Strait of Gibraltar were to close in any month, with Spain experiencing its worst declines should a disruption occur in September. Marine traffic through the Strait of Malacca was also significantly impacted when any of the three chokepoints studied were closed.

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U	U	U	UU	68	19b. TELEPHONE NUMBER *(include area code)* (937) 255-6565, x4326; john.miller@afit.edu