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Modeling Economic Impacts of the Inland Waterway Transportation System

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Modeling Economic Impacts of the Inland Waterway Transportation System

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in Engineering

by

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Abstract

The inland waterway transportation system of the United States (U.S.) handles 11.7 billion tons of freight annually and connects the heartland of the U.S. with the rest of the world by providing a fuel-efficient and environmentally friendly mode of transportation. This dissertation aims to create decision support tools for maritime stakeholders to measure the economic impacts of the inland waterway transportation systems under real world scenarios including disruptions, demand changes, port expansion decisions, and channel deepening investments. Monte Carlo simulation, system dynamics, discrete-event simulation, agent-based modeling, and multiregional input-output modeling techniques are utilized to analyze the complex relationships between inland waterway transportation system components and regional economic impact factors. The first research contribution illustrates that the expected duration of a disruption determines whether decision makers are better off waiting for the waterway system to reopen or switching to an alternative mode of transportation. Moreover, total disruption cost can be reduced by increasing estimation accuracy of disruption duration. The second research contribution shows that without future investment in inland waterway infrastructure, a sustainable system and associate economic impacts cannot be generated in the long-term. The third research contribution illustrates that investing in bottleneck system components results in higher economic impact than investing in non-bottleneck components. The developed models can be adapted to any inland waterway transportation system in the U.S. by utilizing data obtained by publically available sources to measure the economic impacts under various scenarios to inform capital investment decisions and support an economically sustainable inland waterway transportation system.

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1. INTRODUCTION

This dissertation investigates the economic impacts of inland waterway transportation systems under real world scenarios including disruptions, demand changes, port expansion decisions, and channel deepening investments. The decision support tools presented in this dissertation can assist maritime transportation decision makers such as the United States (U.S.) and State departments of transportation (DOTs), U.S. Army Corps of Engineers (USACE), U.S. Coast Guard (USCG), other maritime agencies, and private investors in making well-informed investment decisions related to inland waterway transportation infrastructure to maximize economic benefits of these systems.

1.1 Research Motivation

The maritime transportation system is critical to global trade. More than ninety-nine percent of the U.S. overseas trade in terms of volume and sixty-two percent in terms of value is carried by maritime vessels (MARAD, 2012). Maritime transportation adds more than $649 billion to the U.S. gross domestic product (GDP) each year (MARAD, 2012). Additionally, more than $212 billion in taxes are collected from maritime transportation-related activities, and over 13 million people are employed as a result of maritime activities (MARAD, 2012). Another benefit of maritime transportation is an annual transportation savings of $7 billion in the U.S. from the usage of the maritime mode in place of more costly modes such as rail and highway (USACE, 2009). Other benefits of maritime transportation are emitting less air and noise pollution and operating as a safer mode of transportation compared to other modes (Michigan Technological University, 2006).

Figure 1 Navigable Waterway Transportation Systems (USACE, 2010)

A vital part of the maritime transportation system is the navigable inland waterways. Figure 1 shows a mapping of the inland waterway transportation system of the United States. The U.S. inland waterway transportation system consists of more than 12,000 miles of navigable inland waterways and connects thirty-eight states (USACE, 2005). In 2009, the primary commodities that were shipped on the inland waterways were coal and petroleum and petroleum products, thirty percent and twenty-seven percent tonnage transported respectively (USACE, 2012). Other commodities commonly transported via the inland waterways include crude materials, food and farm products, and chemicals (USACE, 2012). Furthermore, as illustrated in Figure 2, inland waterway transportation is recognized as the transportation mode with the cheapest bulk rate but is also the slowest mode and the mode with most limited connections given the predetermined natural flow of the waterways. In contrast, airway and highway provides the best delivery speed and best connections respectively.

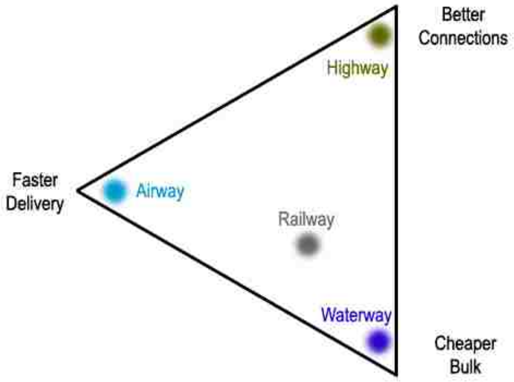

Figure 2 Comparison of Different Modes of Transportation (MoDOT, 2006)

Shipping on the inland waterway transportation system leads to an annual transportation savings of $7 billion in the U.S. (USACE, 2009) because transportation cost by barge is lower than transporting by rail or truck. The cost of one ton-mile (moving one ton of freight for a mile) is 0.72 cents with a barge, 2.24 cents with rail, and 26.62 cents with a large semi truck.

In addition, inland waterway transportation is more fuel efficient than other modes of transportation and has lower air emissions (USACE, 2009). Texas Transportation Institute (TTI) stated that one gallon of fuel can move one ton of freight 155 miles by truck, 436 miles by rail, and 576 miles by barge (2007).

In terms of cargo capacity, Iowa Department of Transportation (IDOT) reported that one barge can carry 1,500 tons, which is equivalent to the capacity of 15 railcars or 58 large semi-trucks, as shown in Figure 3 (2008).

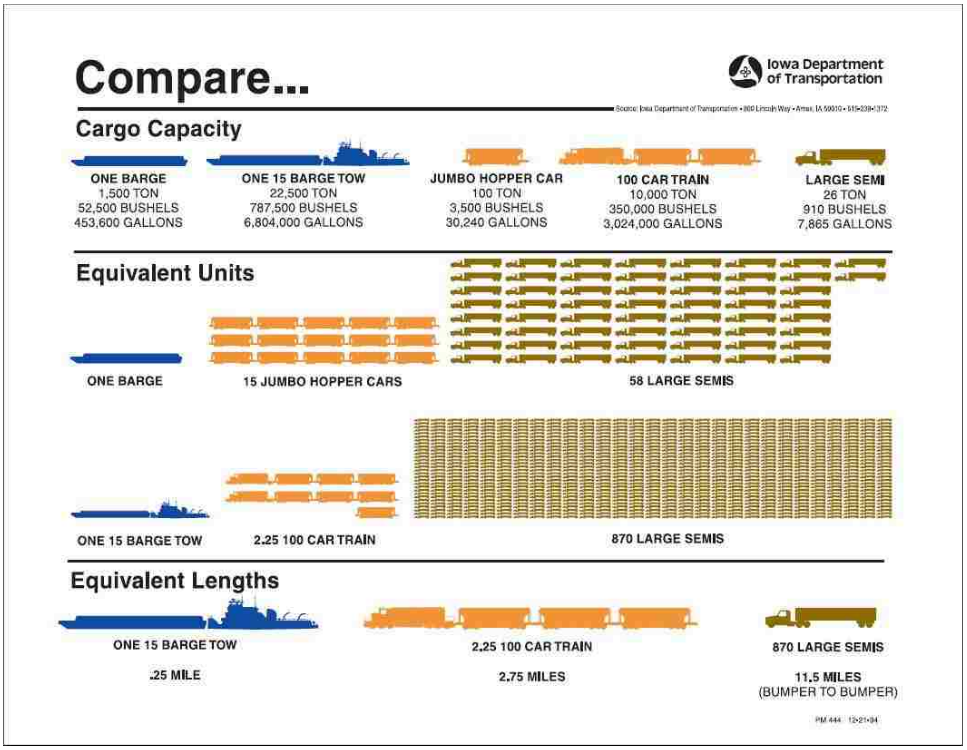

Figure 3 Comparison of Cargo Capacity (IDOT, 2008)

Furthermore, shipping freight via the inland waterway transportation system results in fewer fatalities than shipping via railroads or trucks. One fatality occurring on navigable inland waterways is equivalent to 22.7 fatalities on railroads and as many as 155 fatalities on roadways (MARAD, 2008). One injury occurring in navigable inland waterways is equivalent to 125 injuries occurring on railroads and as many as 2,171 injuries occurring on truck freight (MARAD, 2008).

Another advantage of inland waterway transportation is that it relieves congested roads and railroads. For example, the usage of waterways avoids over fifty-one million truck trips per year (ASCE, 2013). Disruptive events on the inland waterway transportation system can cause significant economic losses, not only for individual companies but also for the total economy of a region or country. If the inland waterway transportation system is disrupted due to a temporary port closure or low water level, commodities cannot be transported as planned. In 2012, *USA*

Today reported that, due to low water levels on the Mississippi River, commodities of over $7 billion were delayed (Keen, 2012). Therefore, it is important for inland waterway transportation stakeholders to understand the economic impacts of normal operations and potential economic impacts due to disruptive events.

1.2 Research Objectives

The primary goal of this research is to develop decision support tools for maritime stakeholders to understand the relationships among inland waterway transportation system components and to measure the economic impacts of real world scenarios including disruptions, demand changes, port expansion decisions, and channel deepening investments.

The research objectives are as follows:

Research Objective 1: Our research objective is to better understand the impacts of disruption duration, estimation, and commodity type on economic impact factors related to the inland waterway transportation system. Predicting economic impacts of inland waterway disruption decisions enables system stakeholders to increase their preparedness and potentially reduce economic losses. Our approach is implemented on an illustrative case study of the McClellan-Kerr Arkansas River Navigation System (MKARNS). The approach is generalizable to any navigable inland waterways to support economic resilience of these systems. This study has been published on *The Engineering Economist* journal and presented in Chapter 3 of this dissertation.

Research Objective 2: We developed a maritime transportation simulator (MarTranS) to better understand the relationships among the inland waterway transportation system components such as ports, locks/dams, navigation channels, commodities, alternative modes of transportation, supply and demand nodes and regional economic impact factors, which is discussed in Chapter 4. This model will enhance investment decision making capabilities for maritime transportation stakeholders.

Research Objective 3: In Chapter 5, we used MarTranS developed in Chapter 4 to study multiple real world scenarios such as economic impacts from the Panama Canal Expansion, channel deepening investments, port expansions, lock/dam rehabilitation investments, and lock/dam scheduled and unscheduled unavailability disruptions.

1.3 Research Methodology

The methodology is organized around the three research objectives:

- Literature Review: A comprehensive literature review is conducted in the field of economic analysis of the maritime transportation system. The completed literature review indicates that there is a need for a decision support tool to estimate the economic impacts of the inland waterway transportation system operations and disruptions to support positive economic outcomes. Our literature review also provides a concrete foundation for the developed methodologies.
- Methodology for Research Objective 1: To assess the economic impacts of navigable inland waterway operations and disruptions, we developed a Monte-Carlo simulation model to assess economic impacts under various disruption scenarios including multiple disruption durations, estimation accuracy levels, and commodity types. We defined disruption durations based on real disruptions discussed in Chapter 3 as short-term (10 days), medium-term (60 days), and long-term (180 days) durations. For each scenario, there are two decision alternatives, the waterway reopens or the cargo remains on the waterway or move to an alternative mode of transportation. Each scenario considers three

possible disruption duration estimation outcomes; accurate estimation (A.E.), overestimation (O.E.), and underestimation (U.E.).

- Methodology for Research Objective 2: MarTranS which integrates agent-based modeling, discrete-event simulation, and system dynamics is developed to better understand the relationship between inland waterway transportation system components and regional economic impact factors. The key components are defined in MarTranS include ports, locks/dams, navigation channel, commodities, alternative modes of transportation, and economic impact factors. In order to estimate long-term economic impacts, a fifty year time frame is considered to study long-term relationships and impacts.
- Research Objective 3: The MarTranS developed in Research Objective 2 is extended to measure the economic impacts of potential scenarios. The scenarios are: 1) base run, 2) Panama Canal Expansion, 3) channel deepening investment, 4) port investment, 5) lock/dam investment, 6) system-wide investment, 7) lock/dam scheduled unavailability disruptions, and 8) lock/dam unscheduled unavailability disruptions.

1.4 Research Contributions

The outcome of this dissertation research contributes to the current literature as well as provide practical decision support tools to maritime stakeholders to inform better inland waterway transportation system investment decisions.

In Research Objective 1, we developed a simulation-based modeling approach to measure the economic impacts of disruption decisions in the inland waterway transportation system. By changing the model parameters, our methodology can be adapted to different study regions, disruption durations, and disruption scenarios. The model parameters can be gathered from publicly available sources or researchers can integrate primary data sources into our model. To our knowledge, this research is the only work that comprehensively investigates the importance of disruption duration estimation on the total disruption costs, transportation, penalty, and holding costs related to navigable waterways. Furthermore, our system-wide holistic approach will help to better inform the true value of an inland waterway transportation system instead of valuing discrete waterway infrastructure, which can assist transportation authorities to allocate available capital funds among investment alternatives.

In Research Objective 2, our MarTranS can help maritime transportation stakeholders to better understand the relationships between inland waterway transportation system components and regional economic impact factors. Understanding these relationships can help stakeholders make better inland waterway infrastructure investment decisions to maximize economic benefits related to economic impact factors.

In Research Objective 3, MarTranS is used to conduct real world scenario analysis to help inland waterway stakeholders to understand the economic impacts of these potential scenarios and better inform future investment decisions.

1.5 Organization of Dissertation

Chapter 1 introduces the inland waterway transportation system and presents the motivation and research objectives of this dissertation. Chapter 2 illustrates our comprehensive literature review which includes two published conference proceedings entitled “A Review of Economic Impact Analysis in Maritime Transportation” published in the *Proceedings of American Society for Engineering Management 2013 International Annual Conference* (Oztanriseven & Nachtmann, 2013) and “A Review of System Dynamics in Maritime Transportation” published in the *Proceedings of the 2014 Industrial and Systems Engineering*

Research Conference (Oztanriseven et al., 2014). Chapter 3 is published in *The Engineering Economist* journal and entitled “Economic Impact Analysis of Inland Waterway Disruption Decisions” (Oztanriseven & Nachtmann, 2016). MarTranS is discussed in Chapter 4, and the navigable inland waterways scenario analysis is presented in Chapter 5. The overall conclusions and future work of this dissertation are discussed in Chapter 6. Transportation Research Part B: Methodological and Maritime Policy are two journals being considered to publish the studies discussed in Chapter 4 and Chapter 5 respectively.

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2. LITERATURE REVIEW

2.1 A Review of Economic Impact Analysis in Maritime Transportation Disruption [1]

2.1.1 Introduction

Our literature review consists of twenty-eight research papers that were written by academic institutions and consulting firms. These studies are then categorized into different classes described as economic analysis methodology used, affected region, source of economic impact, economic indicators used, disruption case scenario, types of disruption studied, and alternative mode of transportation and rerouting considerations. Therefore, our review will assist current and future scholars in the field of analysis of maritime transportation. Our review focuses on maritime transportation, economic analysis, input-output models, and associated disruptive events.

2.1.2 Economic Analysis Methodology Used

An important extension of economic impact studies is the research field of disruptive events in transportation and their economic impacts. Disruptive events can be "natural disasters, accidents, terrorism, war, political and economic instability, supply unavailability, transportation delays, and labor strikes or conflicts" (Figliozzi & Zhang, 2009, p.3). It also includes research about economic impacts of disruptive events in the field of transportation.

As shown in Table 1, the most commonly used economic models are Impact Analysis for Planning (IMPLAN), Inoperability Input-output Models, and the Regional Input-output Modeling System (RIMS II). Our review of the relevant literature reveals that there is little

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[1] Published in *Proceedings of the2013 ASEM International Annual Conference* (Oztanriseven & Nachtmann, 2013)

agreement among scholars regarding which method to use for economic analysis of maritime transportation and associated disruptions.

To measure the economic impact, Leontief developed an input-output model in 1941 (Leontief, 1986). His approach was and is today still widely used (A. Strauss-Wieder, Inc., 2011). The main idea of Leontief's model is that there exists a strong relationship between one industry's input and its output (Jung et al., 2009). In addition, the input-output model is a "static equilibrium model" (U.S. Department of Commerce, 1997) and provides only a "snapshot" of "technical requirements and industry relationships" at a specific point in time (A. Strauss-Wieder, Inc., 2011). Leontief's economic impact matrix is the foundation of several new models developed by different researchers. Over time, researchers developed and extended the original idea of Leontief's input-output model. Thus, today a broad variety of economic input-output models exists and is implemented in studying economic impacts in maritime transportation as shown in Table 1.

Table 1 Economic Analysis Methodology Used

	Model	Description	Author(s)
Input-output (IO) Models	IMPLAN Based Models	Impact Analysis for Planning	Folga et al. (2009)
		National Interstate Economic Model (NIEMO)	Gordon et al. (2005)
			Gordon et al. (2008)
			Park et al. (2008)
		TransNIEMO	Gordon et al. (2008)
	Inoperability IO Models	DMIOM	MacKenzie et al. (2011)
		Inoperability IO Model	Jung et al. (2009)
		Risk-based Multi-Regional Inoperability IO Model	Pant et al. (2011)
	RECON	The Rutgers Economic Advisory Service IO Model	A. Strauss-Wieder, Inc. (2011)
	REIMs	Multi-Regional Commodity Flow Model	Okuyama et al. (1999)
	REMI	Regional Economic Models	Economic Res. Assoc. (2007)
	RIMS II	Regional IO Modeling System	Scott & Associates (2008)
			Martin Associates (2006)
			Nachtmann (2001)
			Richardson & Scott (2004)
	Rural Inland Waterways Kit	The extension of MARAD Model	Hamilton et al. (2000)
	SCPM	Southern California Planning Model	Gordon et al. (2005)
			Gordon et al. (2008)
			Rosoff & Winterfeldt (2007)
	Other IO Models	Canada IO Tables	InterVIDTAS Inc. (2008)
		IO Multipliers	Colegrave et al. (2008)
		Singapore IO Tables	Toh et al. (1995)
		Taiwan IO and Linear Programming Model	Wang & Miller (1995)
		Welsh IO Tables	Bryan et al. (2006)
Other Models	DEA	Date Envelopment Analysis	Xuemei (2011)
	Discrete Choice Model	Decision Tree Model Combining Discrete Choices	Qu & Meng (n.d.)
	Logit Model	Based on Consumer Behavior Theory	Figliozzi & Zhang (2009)
	MOBILE Model	By United States Environmental Protection Agency	Chatterjee et al. (2001)
	SIERRA	System for Import/Export Routing and Recovery Analysis	Jones et al. (2011)
	Spatial Equil. Model	Integrated Grain Transportation Model (IGTM)	Kruse et al. (2011)

2.1.3 Affected Region Studied

When conducting an economic impact analysis, the affected region must be clearly defined (U.S. Department of Commerce, 1997). Based on the purpose of the study, scholars may define the affected region from regional to global. A listing of study regions found in our literature review is presented in Table 2. As shown in Table 2, the regional studies can be conducted at the city, county, economic region, state, or multi-state levels (MacKenzie et al., 2011). Some scholars conduct economic analyses at the national level. Other scholars define their affected region on an international level or as combination of regional, national, and global levels.

Table 2 Affected Region Studied

Level	Affected Region Detail	Author(s)
Regional	2 cities and 5 counties in California	Gordon et al. (2005)
	27 highway sections	Chatterjee et al. (2001)
	31 counties in New York, New Jersey, and Pennsylvania	A. Strauss-Wieder, Inc. (2011)
	Auckland	Colegrave et al. (2008)
	Congressional districts	Kruse et al. (2011)
	Arkansas	Nachtmann (2001)
	Los Angeles Metropolitan Area	Rosoff & Winterfeldt (2007)
	Multiple states	MacKenzie (2011), Pant et al. (2011)
	San Diego county and California	Economic Research Associates (2007)
	Shanghai	Xuemei (2011)
	South Wales	Bryan et al. (2006)
	Illinois	Folga et al. (2009)
	Vancouver, Oregon and Washington	Martin Associates (2006)
National	Republic of Singapore	Toh et al. (1995)
	United States	Park et al. (2008)
International	International Supply Chain	Lewis et al. (2006)
	International Trade in the United States	Jung et al. (2009)
	United States and 46 other countries	Jones et al. (2011)
Combination	British Columbia and Canada	InterVIDTAS Inc. (2008)
	Houma Metropolitan Statistical Area and United States	Loren C. Scott & Associates (2008)
	Regional, National, and Global	Gordon et al. (2008)
	Louisiana and the United States	Richardson & Scott (2004)

2.1.4 Source of Economic Impact

The sources of the economic impact analysis studied in the maritime transportation literature are shown in Table 3. A single port, multiple ports, a single lock, multiple straits, and inland waterway infrastructure are the classification levels for the source of economic impact for maritime transportation in the reviewed literature.

Table 3 Source of Economic Impact

Source of Economic Impact	Author(s)
Single Port	A. Strauss-Wieder, Inc. (2011)
	Economic Research Associates (2007)
	Gordon et al. (2008)
	Lewis et al. (2006)
	Loren C. Scott & Associates (2008)
	MacKenzie (2011)
	Martin Associates (2006)
	Pant et al. (2011)
	Toh et al. (1995)
	Xuemei (2011)
Multiple Ports	Bryan et al. (2006)
	Colegrave et al. (2008)
	Gordon et al. (2005)
	Gordon et al. (2008)
	InterVIDTAS Consulting Inc. (2008)
	Park et al. (2008)
	Rosoff & Winterfeldt (2007)
Single Lock	Chatterjee et al. (2001)
	Kruse et al. (2011)
Multiple Straits	Qu & Meng (n.d.)
Inland Waterway Infrastructure	Folga et al. (2009)

2.1.5 Economic Indicators Used

According to the reviewed literature, five major economic indicators (Gross Domestic Product (by State), Gross Output, Employee Earnings, Employment, and Tax Revenue) are found and identified in Table 4.

Table 4 Economic Indicators Used

Economic Indicator	Synonyms/ Components	Author(s)
Gross Domestic Product (by State)	GDP ($)	Colegrave et al. (2008)
		Gordon et al. (2008)
		Xuemei (2011)
	GDP ($)/Value-added ($)	InterVIDTAS Cons. Inc. (2008)
	GDP ($)/Value-added ($)/National Income ($)	Wang & Miller (1995)
	Gross Regional Product ($)/Output ($)	Gordon et al. (2005)
	Gross State Product (GSP) ($)	Nachtmann (2001)
	Value Added Gross Regional Product (GRP) ($)	Economic Res. Assoc. (2007)
Gross Output	Economic Output ($)/Output ($)/Gross Revenue ($)	InterVIDTAS Consult.. (2008)
	Economic Value ($)	Martin Associates (2006)
	Gross Output ($)	Wang & Miller (1995)
	Industry Output ($)	Pant et al. (2011)
	Output ($)	Colegrave et al. (2008)
		Economic Res. Assoc. (2007)
		Gordon et al. (2008)
		Hamilton et al. (2000)
		Toh et al. (1995)
	Sales ($)	Loren C. Scott & Assoc. (2008)
		Richardson & Scott, 2004
	Spending ($)/Output ($)	Bryan et al. (2006)
	Total Business Income/Revenue	A. Strauss-Wieder, Inc. (2011)
Employee Earnings	Earnings ($)	Richardson & Scott (2004)
	Employee Earnings ($)	Nachtmann (2001)
		Loren C. Scott & Assoc. (2008)
	Household Incomes ($)	Colegrave et al. (2008)
	Income ($)	Hamilton et al. (2000)
		Toh et al. (1995)
	Personal Income ($)	Economic Research Associates (2007)
		Martin Associates (2006)
	Total Earnings/Personal Income	A. Strauss-Wieder, Inc. (2011)
	Wage ($)	Wang & Miller (1995)
	Wages ($)/Payroll ($)	InterVIDTAS Consulting (2008)

Table 4. Economic Indicators Used (Cont'd)

Economic Indicator	Synonyms/ Components	Author(s)
Employment	Employment	A. Strauss-Wieder, Inc. (2011)
		Economic Res. Assoc.(2007)
		Hamilton et al. (2000)
		Loren C. Scott & Assoc. (2008)
		Nachtmann (2001)
		Richardson & Scott (2004)
		Toh et al. (1995)
	Employment (Full-time-equivalents jobs)	Colegrave et al. (2008)
		Bryan et al. (2006)
	Jobs	Gordon et al. (2008)
		Martin Associates (2006)
	Jobs (person-years)	Gordon et al. (2005)
		InterVIDTAS Consulting (2008)
Tax Revenues	Indirect Business Taxes ($)	Hamilton et al. (2000)
	Payroll Tax, Property Tax, Sales Tax, Transient Occupancy Tax, and Business License Tax	Economic Res. Assoc. (2007)
	Sales Taxes ($)	Loren C. Scott & Assoc. (2008)
	State and Local Taxes ($), Federal Taxes ($)	Martin Associates (2006)
	Taxes Paid by Employers and Employees, Taxes Paid by the Port Authority, Taxes Paid by Cruise Passengers, Crew, and Cruise Lines	InterVIDTAS Consulting (2008)
	Total Local Tax ($), Total State Tax($), Total Federal Tax ($)	A. Strauss-Wieder, Inc. (2011)

2.1.6 Disruption Case Scenario

Because of the uncertain nature of disruptions, it is necessary to make assumptions to conduct an economic assessment of future disruptions. Thus, many scholars study hypothetical case scenarios. Table 5 indicates which scholars conduct a hypothetical scenario analysis and which scholars conduct a disruption analysis on a real world incident.

Table 5 Economic Analysis of Disruptions

Disruption Case Scenario	Author(s)
Hypothetical	Chatterjee et al. (2001)
	Figliozzi & Zhang (2009)
	Folga et al. (2009)
	Gordon et al. (2005)
	Gordon et al. (2008)
	Jones et al. (2011)
	Kruse et al. (2011)
	Lewis et al. (2006)
	MacKenzie et al. (2011)
	Okuyama et al. (1999)
	Pant et al. (2011)
	Park et al. (2008)
	Qu & Meng (n.d.)
	Richardson & Scott (2004)
	Rosoff & Winterfeldt (2007)
	Wang & Miller (1995)
Real	Jung et al. (2009)
	Loren C. Scott & Associates (2008)

2.1.7 Type of Disruption Studied

Based on the scope, scholars conducted a disruption economic impact analysis for either a specific type of disruptive event or for a disruption in general. Specific types of disruption analysis can focus on natural or man-made disruptions. These classifications are presented in Table 6.

Table 6 Types of Disruption Studied

Type of Disruption Studied	Detail (if any)	Author(s)
Natural Disaster	Earthquake	Okuyama (1999)
	Erosion	Richardson & Scott (2004)
Man-made	Labor Strike	Jung et al. (2009)
	Lockout	Park et al. (2008)
	Terrorist Attacks	Gordon et al. (2005)
		Gordon et al. (2008)
		Rosoff & Winterfeldt (2007)
General	▨	Chatterjee et al. (2011)
		Figliozzi & Zhang, (2009)
		Folga et al. (2009)
		Jones, et al. (2011)
		Kruse et al. (2011)
		Lewis et al. (2006)
		Loren C. Scott & Associates (2008)
		Qu & Meng (n.d.)
		Wang & Miller (1995)
Other	Sudden Port Closures	MacKenzie et al. (2011)
	Process Disruptions of Ports	Pant et al. (2011)

2.1.8 Alternative Modes of Transportation and Rerouting

During a maritime transportation disruption, decision makers have the option of rerouting to an alternative mode of transportation. Some of the papers consider an alternative mode of transportation and/or rerouting opportunities, while others do not as shown in Table 7.

Table 7 Alternative Mode of Transportation and Rerouting

Alternative Mode of Transportation and	Author(s)
Yes	Chatterjee et al. (2001)
	Figliozzi & Zhang, (2009)
	Folga et al. (2009)
	Gordon et al. (2008)
	Jones et al. (2011)
	Kruse et al. (2011)
	MacKenzie et al. (2011)
	Okuyama et al. (1999)
	Park et al. (2008)
	Qu & Meng (n.d.)
No	Gordon et al. (2005)
	Jung et al. (2009)
	Lewis et al. (2006)
	Loren C. Scott &
	Pant et al. (2011)
	Richardson & Scott (2004)

2.1.9 Conclusions and Future Work

This research presents the current body of knowledge regarding economic impact analysis within the maritime transportation field and associated disruption impacts. The maritime transportation system is important to decreasing total transportation cost, decreasing risk by diversification of transportation modes, mitigating fatalities and injuries, reducing carbon emission, increasing public recreational area access and expanding total capacity of the Nation's transportation system. Supporting future research to facilitate usage of the U.S. maritime transportation system is important. In addition to describing the motivation of our ongoing research, this literature review can assist other scholars in their current and future research in this field. In particular, engineering managers working in the maritime transportation field can utilized the knowledge base provided here as a starting point for developing their economic analyses. The guidance and lessons learned from these earlier studies provides a sound starting point for developing a new framework to analyze the economics of maritime transportation systems. The literature review presented here has provided a foundation for an economic impact analysis of inland waterway transportation conducted for the State of Arkansas.

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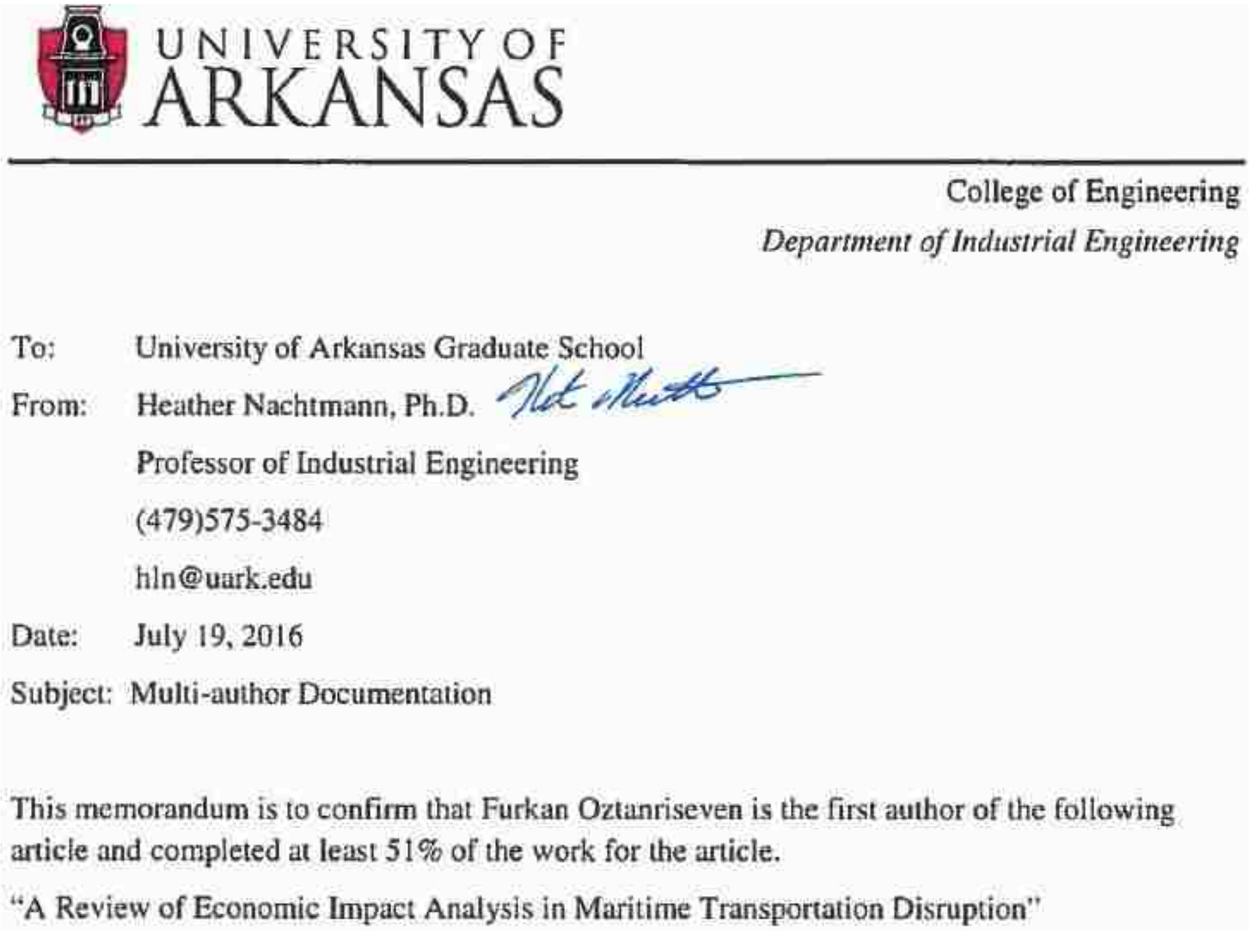
Appendix 1



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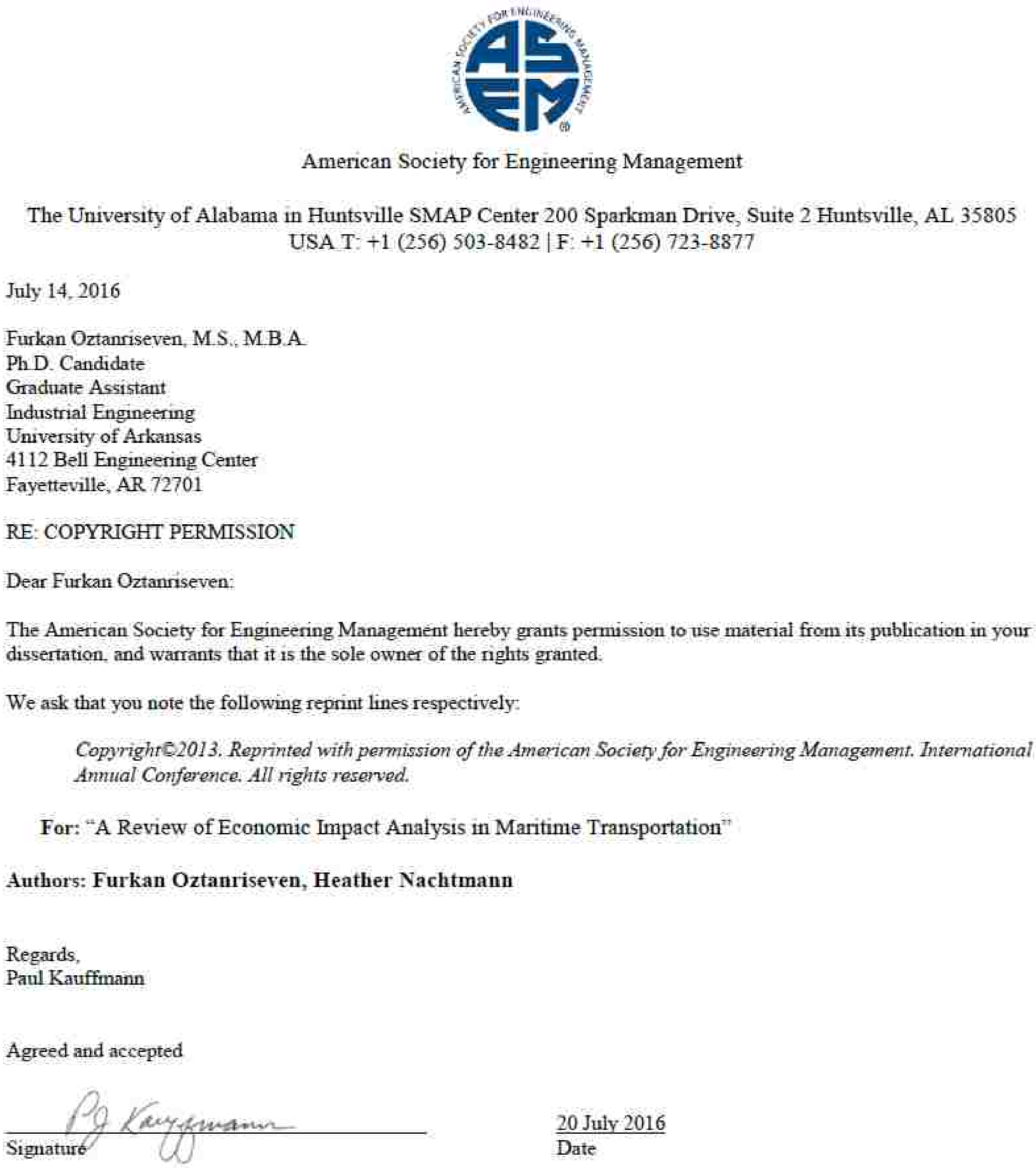
"A Review of Economic Impact Analysis in Maritime Transportation Disruption"

Appendix 2



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2.2 A Review of System Dynamics in Maritime Transportation[2]

2.2.1 Introduction

The United States' "marine highways" are an important component of the nation's transportation system, which carry one-twelfth of the total national freight volume (Stern, 2013). The ability of North American ports to efficiently handle growing cargo volumes has a major impact on the trading capabilities and economies of the region as a whole. U.S. ports handle $5.5 million worth of goods every day and 2.5 billion tons of cargo every year. This volume is expected to double in the next fifteen years (American Association of Port Authorities, 2007). Therefore, an efficient and effective maritime transportation system can have widespread economic and societal impacts. Thus, the aim of this research is to explore the feasibility of using SD to study and support an efficient MTS.

Developed by Jay Forrester in the late 1950s, SD is "a methodology for studying and managing complex feedback systems." Forrester (Forrester, 1961) describes an information feedback system existing whenever "…the environment leads to a decision that results in action which affects the environment and thereby influences future decisions" (p. 14). Moving away from the conventional approach of viewing system performance and behavior as merely the result of events and their causes, SD emphasizes the interactions between components of a system (Kirkwood, 1998). As an application of systems thinking, SD seeks to identify the underlying structure of a system to gain insight into patterns of behavior, focusing on how components of a system interact and understanding the roles each component plays rather than concentrating on specific events. This allows stakeholders to design policies that seek to

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eliminate unwanted patterns of behavior through modifying the underlying system structure, rather attempting to mitigate the events themselves, which can lead to a host of other unintended consequences (Kirkwood, 1998). We anticipate that this system structure exists in the maritime logistics system. This literature review is the result of a pilot study designed to evaluate methodologies and mechanisms for creating a long-term, sustainable MTS (Long et al., 2014). This work seeks to advance the SD body of knowledge in logistics infrastructure design and implementation. Existing models have been criticized for maintaining the status quo; new approaches to infrastructure development are considered essential in order for the U.S. to remain competitive in the global economy (Urban Land Institute, 2008).

2.2.2 Literature Review

Evidence that SD can be used to study and improve the MTS is found in the literature. Our literature review focuses on the applicability of SD in the field of maritime transportation and indicates that SD is applied to many components of the MTS including maritime disruption studies, port-related studies, and vessel-related studies among others.

2.2.2.1 Maritime Disruption System Dynamics Studies

Disruptive events such as the 9/11 terrorist attacks, 2002 Los Angeles/Long Beach lockout, and Hurricane Katrina increased the awareness of policy makers and researchers about the importance of maritime security. Lattila and Saranen (Lattila & Saranen, 2011) showed that SD could be used to study the impact of general disruptive events in the MTS. More specifically, the authors used SD to investigate potential risk scenarios on the Gulf of Finland and illustrated that a disruption results in export loss (in tons) (Lattila & Saranen, 2011). When a disruption occurs in the MTS, the system needs to recover to the pre-disruption throughput level. This process is described as the resiliency of a system. In general, resiliency has two dimensions, vulnerability and adaptive capacity (Dalziell & McManus, 2004). Omer et al. (2012) and Croope and McNeil (2011) used SD to study the resiliency of the MTS. Constructing a resilient MTS can minimize potential losses. Research shows that maritime ports are vulnerable against disruptions due to their strategic geographic locations, and a disruption will result in negative local and global impacts (Omer et al., 2012). In a similar vein, Croope and McNeil (2011) used SD to study the resiliency of critical infrastructures and disruption-related costs. Transportation systems in general and specifically the MTS are comprised of critical infrastructure (Clinton, 1998). Critical infrastructures are the core elements of the Nations' economic and societal assets (Croope & McNeil, 2011).

To decrease vulnerability and increase resiliency, security policies are established by governments and private entities. Yeo et al. (2013) investigated the impacts of security policy changes. Their research illustrated that new security measures can have both positive and negative impacts on cost and port efficiency (Yeo et al., 2013). To summarize, disruptions negatively impact the MTS. The literature shows that SD has been used to model disruption complexities and uncertainties in the MTS.

2.2.2.2 Port-Related System Dynamics Studies

A portion of the maritime transportation system dynamics (MTSSD) literature focuses on the implementation of SD to conduct port-related studies. Dundovic et al. (2009), Dvornik et al. (2006), and Munitic et al. (2003) applied a SD model to study port-handling processes. These studies considered loading and unloading operations from ship to shore, transfer operations from shore to wagons and trucks, and warehouses. Similarly, Cheng et al. (2010) focused on the berth and yard operations, which are complex, and handled separately in terms of planning and decision-making. Their research used SD to analyze these two interdependent subsystems and their respective impacts on the overall port performance. Overall, SD simulation is a powerful tool to handle the complex port transshipment processes, but only a limited number of SD studies have been conducted for ports (Cheng et al., 2010).

Another extension of port-related SD studies is the investigation of the port economics. For instance, Ho et al. (2008) studied port expansion decision and its economic outcomes. Their study showed that if the expected revenue and throughput cannot be generated, the expansion decision will lead to a financial dilemma. In addition, their study showed that simply increasing the number of ports in a specific region may not result in a positive economic impact because ports need to be supported by other infrastructures such as warehouses and shipping connectivity (Ho et al., 2008). Mingming (2011) illustrated the relationships between port investments, port capacity, economic contribution of ports, and aggregate economy relationship through SD modeling. Li and Wang (2013) analyzed the economic contribution of ports to the regional economy. The authors also integrated an input-output analysis and an econometrics model with their SD simulation. Their integrated methodology is shown to be a powerful tool to analyze port economics (Li & Wang, 2013).

2.2.2.3 Vessel-Related System Dynamics Studies

System dynamics has been used to study the global shipping market in the MTS to understand the behavior of shipping freight rates (Randers & Göluke, 2007). Their model successfully explained the behavior of the tanker market since 1950 by only considering fleet size and fleet utilization data (Randers & Göluke, 2007). Engelen et al. (2009) researched the arbitrage between different vessel types, such as handy, Panamax, and capsize, and explained the correlation of freight rates for different ship segments. Dikos et al. (2006) developed a SD model to use as a decision support tool for freight rates and risk management for the tanker industry.

Wijnolst (1975) focused on the relations between national fleet development and national objectives in developing countries. Wijnolst (1975) considered productivity of ships and investment in new ships.

2.2.2.4 Other MTSSD Studies

Other studies have utilized SD to study the MTS. Schade and Schade (2005) and Fiorello et al. (2010) developed a holistic SD approach. Schade and Schade (2005) integrated five models (transportation, macroeconomic, regional economic, policy, and environmental) into one aggregated model titled ESCOT. The authors developed a sub-model for transportation including water, rail, road, and air that aims to reach a sustainable transportation system and estimates the economic impacts of the German transportation system. Fiorello et al. (2010) built their SD model upon the ESCOT model (Schade & Schade, 2005). Fiorello et al. (2010) considered road, rail, and maritime transportation in their model and measured investments, capacities, and their respective economic outcomes. Videira et al. (2012) also used a qualitative SD approach for maritime policy development which indicates that cooperation between policy-makers and stakeholders is crucial to selecting the best policy.

2.2.2.5 Summary

Our review of the MTSSD literature shows that SD is applicable to studying MTS. Engelen et al. (2009) claimed that SD has a potential of applications in a variety areas of maritime transportation research. In addition, SD has the ability of overcoming the drawbacks of time-series and statistical models (Dikos et al., 2006). SD modeling also takes causality into account, allows what-if scenario analysis, and can be adapted to study fundamental changes in the system. Furthermore, sensitivity analysis can be conducted within the model, which can help maritime stakeholders to better analyze the outcomes of MTS policy changes (Dikos et al., 2006).

2.2.3 Classification of the MTSSD Literature

In this section, we classify the literature review findings to clarify the current body of knowledge and identify future research questions. We classify the literature into study region, types of ports studied, intermodal transportation considered, types of causal relations considered, variable classifications, stock and flow diagram elements, and sensitivity and scenario analysis considerations.

2.2.3.1 Study Region

Table 8 describes the study regions covered in the MTSSD literature. The majority of studies focused on the major ports in Asia. With the exception of two hypothetical studies, the papers investigate real-world components of the MTS.

Table 8 Study Region Classification

Study Region	Explanation	Source
Asia	Most Important Asian Ports: Busan (Korea), Hong Kong (China), Kaohsiung (Taiwan), Shanghai (China), Yokohoma (Japan)	(Omer et al., 2012)
	Korean Ports	(Yeo et al., 2013)
	Port of Hong Kong China’s Pearl River Delta Region	(Ho et al., 2008)
	One of the Container Terminals in Malaysia	(Cheng et al., 2010)
	Port located in Southeastern China	(Mingming, 2011)
	Zhuhai Port (China)	(Li & Wang, 2013)
	Port of Busan (South Korea)	(Park et al., 2005)
North America	Most Important American Ports: Seattle/Tacoma (US), Oakland (US), and Port of Los Angeles/Long Beach (US)	(Omer et al., 2012)
Europe	Port of Sibenik (Croatia)	(Dundovic et al., 2009)
	Gulf of Finland Region	(Lattila & Saranen, 2011)
	Maritime Sustainability Issues in Portugal	(Videira et al., 2012)
	Finnish Ports	(Lattila O. L., 2008)
International	World's Shipping Market	(Randers & Göluke, 2007)
	Atlantic and Pacific Basin	(Engelen et al., 2009)
	Tanker Market for Niver Lines	(Dikos et al., 2006)
Hypothetical	Hypothetical Developing Country	(Wijnolst, 1975)
	Three Harbors named as A, B and C	(Koseler, 2008)

2.2.3.2 Port Type

To further classify the type of MTS studied, we considered the type of port studied in the MTSSD literature. The vast majority of port-related studies focus on seaports (Lattila & Saranen, 2011; Omer et al., 2012; Yeo et al., 2013; Ho et al., 2008; Li & Wang, 2013; Wijnolst, 1975; Park et al., 2005; Lattila O. L., 2008). None of the studies focused on inland waterway ports.

2.2.3.3 Intermodal Transportation Consideration

The third literature classification considers whether or not intermodal transportation is studied. Intermodal transportation studies generally investigate the advantages and disadvantages of the various transportation modes. For instance, bulk freight can be first transported by vessel or barge and then transferred directly to rail car and delivered to the customer. Based on our review, there is limited work that utilizes SD in maritime transportation within an intermodal context (Lattila & Saranen, 2011; Dvornik et al., 2006; Koseler, 2008).

2.2.3.4 Causal Relation Variables

To describe the SD methodological approaches taken, we identify the types of causal relations that are considered in the literature. The variables classified in Table 9 are grouped into seven categories. The most frequently considered causal relation variables are Resource Capacity, Investment, Throughput Generated, and Resource Availability.

Table 9 Causal Relation Variables

Causal Relation	Explanation	Source
Port/Terminal	Security Level	(Yeo et al., 2013)
	Attractiveness	(Yeo et al., 2013;Cheng et al., 2010)
	Competition	(Li & Wang, 2013)
	Reliability	(Yeo et al., 2013)
	Expansion	(Ho et al., 2008)
	Efficiency	(Cheng et al., 2010)
	Burden	(Mingming, 2011)
Time	Ship Service Time	(Koseler, 2008)
	Loading/Unloading Time (Container)	(Cheng et al., 2010)
	Vessel Turnaround Time	(Cheng et al., 2010)
	Vessel Waiting Time	(Cheng et al., 2010)
	Transportation Time	(Koseler, 2008)
	Conjunction Time for Berthing	(Koseler, 2008)
Freight Flow	Throughput Generated (Container, Freight)	(Yeo et al., 2013;Cheng et al., 2010;Ho et al., 2008;Li & Wang, 2013)
	Exported Volume	(Lattila O. L., 2008;Silva et al., 2011)
Transshipment Process	Resource Movements (Crane)	(Cheng et al., 2010)
	Vessel/Ship Arrival	(Dvornik et al., 2006; Munitic et al., 2003; Cheng et al., 2010)
	Occupancy (Berth)	(Dvornik et al., 2006; Munitic et al., 2003; Cheng et al., 2010)
	Speed (Loading/Unloading, Transportation, Forwarding Truck/Wagons)	(Dvornik et al., 2006; Li & Wang, 2013)
Capacity and Capacity Utilization	Resource Capacity (Port/Terminal, Crane, Berth, Seaman, Ship)	(Cheng et al., 2010;Li & Wang, 2013;Wijnolst, 1975;Mingming, 2011;Koseler, 2008)
	Resource Availability (Berth, Warehouse Space, Seaman, Terminal, Technology, Crane, Truck)	(Dvornik et al., 2006; Munitic et al., 2003; Wijnolst, 1975; Koseler, 2008)
	Utilization (Fleet)	(Randers & Göluke, 2007)
	Desired Utilization (Fleet)	(Randers & Göluke, 2007
	Desired Capacity (Ship Building)	(Wijnolst, 1975)

Table 9 Causal Relation Variables (Cont'd)

Causal Relation	Explanation	Source
Monetary/Economic	Cargo Processing Cost	(Yeo et al., 2013)
	Operating Cost	(Cheng et al., 2010)
	Export Industries' Logistics Costs	(Silva et al., 2011)
	Time Charter Rate	(Randers & Göluke, 2007)
	Investment (Port/Terminal, Ship Building Capacity)	(Cheng et al., 2010;Li & Wang, 2013;Wijnolst, 1975;Mingming, 2011)
	Foreign Trade (Export, Import)	(Wijnolst, 1975; Mingming, 2011;Lattila O. L., 2008)
	Maritime Carrier Profit	(Silva et al., 2011)
	Port Economic Contribution (Port-led GDP, Employment)	(Li & Wang, 2013;Mingming, 2011)
	Exchange Rates	(Lattila O. L., 2008)
	Inflation	(Lattila O. L., 2008)
Disruption	Possibility of Security Incident	(Yeo et al., 2013)
	Congestion (Port, Yard, Berth)	(Cheng et al., 2010; Ho et al., 2008)

2.2.3.5 Variable Type

We classify the variable types employed grouped into endogenous, exogenous, and excluded variables as shown in Table 10. In SD modeling, the researcher develops a hypothesis which can explain the phenomena endogenously (Sterman, 2000). The exogenous variables are the ones that are out of the boundaries of the model. Exogenous variables in a SD model are not part of the feedback structure but do impact the system behavior. There are also excluded variables that are not considered in the model. In Table 10, we also illustrate the types of stock, flow rate, and delay variables that are utilized in the MTSSD literature.

Table 10 Variable Classification

Variable Type	Explanation	Source
Endogenous Variables Considered	Domestically Generated Throughput	(Ho et al., 2008)
	Travel Cost and Time	(Fiorello et al., 2010)
	Supply Function	(Dikos et al., 2006; Engelen , 2006)
	Container Inventories	(Koseler, 2008)
	Capacity (Crane, Ocean Carrier)	(Koseler, 2008)
	Empty Container Flows	(Koseler, 2008)
	Loading/Unloading Crane Capacity	(Koseler, 2008)
	Harbor Productivity	(Koseler, 2008)
Exogenous Variables Considered	Container Capacity	(Lattila & Saranen, 2011)
	Throughput that originate from Mainland China and from Taiwan	(Ho et al., 2008)
	Ship Arrival	(Dvornik et al., 2006)
	Demand	(Dikos et al., 2006; Koseler, 2008)
	Export of the Bulk Commodity	(Wijnolst, 1975)
	Price of the Commodity	(Wijnolst, 1975)
	Freight Rate	(Wijnolst, 1975)
Excluded Variables Considered	Urban Public Expenditure Policies on Roads and Rail	(Ho et al., 2008)
	Berthing Conjunction Time	(Koseler, 2008)
	Total Number of Ocean Carriers	(Koseler, 2008)
	Profit	(Koseler, 2008)
	Labor	(Koseler, 2008)
	Transportation Costs	(Koseler, 2008)
	Investment in Technology	(Koseler, 2008)
	Ship Service Time	(Koseler, 2008)
Stock/Level/State Variables	Empty Container Inventories	(Koseler, 2008)
	Container Volume	(Yeo et al., 2013)
	GDP Aggregate	(Li & Wang, 2013; Mingming, 2011)
	Hinterland Backlog	(Lattila & Saranen, 2011)
	Port Throughput/Transshipment	(Ho et al., 2008; Park et al., 2005)
	Cargo on Board and Cargo Delivered	(Engelen , 2006)
	Capacity moved from Another Port	(Lattila & Saranen,2011)
	Port Capacity	(Li & Wang, 2013;Mingming, 2011)
	Ships, Lay-up, Scrap	(Dikos et al., 2006)
	Ships at Ports	(Omer et al., 2012)

Table 10 Variable Classification (Cont'd)

Flow/Rate/Derivative Variables	Ships/Vessels	(Omer et al., 2012; Cheng et al., 2010; Engelen , 2006)
	Containers	(Yeo et al., 2013)
	Empty Containers	(Koseler, 2008)
	Capacity (Cranes, Port)	(Lattila & Saranen, 2011; Mingming, 2011)
	Freight	(Lattila & Saranen, 2011; Ho et al., 2008; Li & Wang, 2013; Park et al., 2005)
	Money	(Li & Wang, 2013;Mingming, 2011)
	New Ship Rate	(Dikos et al., 2006)
	Lay-up Rate	(Dikos et al., 2006)
	Scraping Rate	(Dikos et al., 2006)
Delay/Lag Variables	Demand Lag to Capacity Expansion	(Ho et al., 2008)
	Between the Ordering and the Delivery of the Vessel	(Dikos et al., 2006; Engelen , 2006)
	Between Port Investment and Port Capacity Increase	(Mingming, 2011)

2.2.3.6 Sensitivity and Scenario Analysis

The MTSSD literature is classified in terms of the employment of sensitivity and scenario analysis grouped into disruption-related, capacity-related, and other analyses in Table 11.

Table 11 Sensitivity and Scenario Analysis

Sensitivity and Scenario Analysis	Explanation	Source
Disruption-related	Security Level	(Yeo et al., 2013)
	Disaster Response Time	(Croope & McNeil, 2011)
	Probability of Disruption Occurrence	(Croope & McNeil, 2011)
	Different Port Closures due to Oil Spillage	(Lattila & Saranen, 2011)
Capacity-related	Warehouse Capacity	(Dundovic et al., 2009)
	Ship Capacity	(Dundovic et al., 2009;Koseler, 2008)
	Hinterland Capacity	(Lattila & Saranen, 2011)
	Different Level of Port Expansions	(Ho et al., 2008)
Other	Demand Change	(Randers & Göluke, 2007; Dikos et al., 2006; Lattila O. L., 2008)
	Quay Crane Moves per Hour	(Cheng et al., 2010)

2.2.4 MTSSD Methodology Classification

Since we are investigating SD as a methodological approach to studying the MTS, we also classify the MTSSD literature in the context of methodology descriptors. We grouped the relevant literature into six methodology descriptors including sub-model consideration, model integration, simulation period, software selection, modelling challenges and difficulties, and validation and verification techniques.

2.2.4.1 Model Integration

First, we identify the literature that considered subsystems. Several papers (Croope & McNeil, 2011; Yeo et al., 2013; Dvornik et al., 2006; Munitic et al., 2003; Cheng et al., 2010; Dikos et al., 2006; Fiorello et al., 2010; Videira et al., 2012; Park et al., 2005;Koseler, 2008) considered MTS subsystems that are interconnected with each other. Some scholars considered another type of model integrated with their SD model to analyze their problem of interest. The list of integrated models and corresponding studies are listed in Table 12.

Table 12 Integration of SD with Other Models

Integration with Other Model	Source
Network Optimization	(Omer et al., 2012)
Input-Output	(Li & Wang, 2013)
Econometrics	(Li & Wang, 2013)
Regression	(Park et al., 2005;Lattila O. L., 2008)

2.2.4.2 Simulation Period Employed

The MTSSD literature in Table 13 is classified according to the simulation period employed.

Table 13 Simulation Period Employed

Simulation Period	Explanation	Source
Hours	720 and 1500 Hours	(Lattila & Saranen, 2011)
Days	2 and 4 Days	(Croope & McNeil, 2011)
	360,750, and 1500 Days, Time Step=1day	(Koseler, 2008)
	250 and 730 Days	(Lattila & Saranen, 2011)
Months	170 Months, Time Step=1 Month	(Engelen , 2006)
	72 Time Periods (i.e. Months), Time Step=0.25 (i.e. weeks)	(Engelen et al., 2009)
Years	1970 - 2020, Time Step=1 Year	(Yeo et al., 2013)
	10 Years	(Ho et al., 2008)
	1990-2050	(Fiorello et al., 2010)
	2007-2009, Time Step=1 Year	(Mingming, 2011)
	2007-2025	(Li & Wang, 2013)
	1950-2010, Time Step=1 Year	(Randers & Göluke, 2007)
	1980-2002, Time Step=1 Quarter	(Dikos et al., 2006)
	1970-2010, Time Step=1 Year	(Wijnolst, 1975)
	1998-2007	(Park et al., 2005)
	2010-2030	(Lattila O. L., 2008)

2.2.4.3 Software Utilized

The list of software products utilized in the reviewed MTSSD literature is shown in Table 14.

Table 14 Software Utilized

Software	Source
Vensim	(Omer et al., 2012; Yeo et al., 2013;Li & Wang, 2013;Fiorello et al., 2010;Lattila O. L., 2008;Engelen , 2006;Santella & Steinberg, 2009)
Powersim	(Dundovic et al., 2009;Dvornik et al., 2006; Munitic et al., 2003;Dikos et al., 2006;Park et al., 2005)
Stella	(Croope & McNeil, 2011)
iThink	(Cheng et al., 2010)
DYNAMO	(Wijnolst, 1975)

2.2.4.4 Modeling Challenges

We identified two major classifications of modelling challenges found in the literature as data-related and complexity-related challenges shown in Table 15.

Table 15 Modeling Challenges

Challenge	Explanation	Source
Data-related	Availability	(Engelen et al., 2009;Dikos et al.,2006; Videira et al., 2012; Lattila O. L., 2008;Santella & Steinberg, 2009)
	Accuracy/Reliability	(Ho et al., 2008; Dikos et al., 2006)
	Transformations	(Lattila O. L., 2008)
Complexity-related	Keep the Model Size Manageable	(Randers & Göluke, 2007; Fiorello et al., 2010)
	Define Metric(s) to Capture System Performance	(Omer et al., 2012; (Croope & McNeil, 2011)
	Identify Various Types of Interdependencies/Feedbacks	(Lattila & Saranen, 2011;Croope & McNeil, 2011;Li & Wang, 2013; Santella & Steinberg, 2009)
	Quantify the Dependencies between the Variables	(Ho et al., 2008; Engelen , 2006;Santella & Steinberg, 2009)
	Many Assumption Requirements	(Croope & McNeil, 2011)
	Capture Changes in the System Over Time	(Croope & McNeil, 2011)
	Entities Possess Characteristic of Heterogeneity	(Silva et al., 2011)
	Involve Broad Stakeholder Groups and Lack of Information	(Videira et al., 2012)

2.2.4.5 Validation/Verification Techniques

Table 16 classifies the validation/verification techniques that are utilized in the MTSSD literature. The most common validation/verification technique is comparing model outputs with historical data and implementing a case study.

Table 16 Validation/Verification Techniques

Validation/Verification	Source
Compare with Historical Data and Implement a Case Study	(Croope & McNeil, 2011; Yeo et al., 2013; Dundovic et al., 2009; Cheng et al., 2010;Li & Wang, 2013;Randers & Göluke, 2007; Engelen et al., 2009; Dikos et al., 2006;Mingming, 2011;Lattila O. L., 2008;Santella & Steinberg, 2009)
Sensitivity Analysis	(Ho et al., 2008;Park et al., 2005;Koseler, 2008;Santella & Steinberg, 2009)
Expert Reviews	(Santella & Steinberg, 2009)

2.2.5 Conclusion and Future Work

This paper presents a review of the MTSSD literature and illustrated the wide variety of SD applications in MTSSD. The literature shows that SD models are successfully utilized to describe the complexity of MTS. Our classification of the MTSSD literature indicates that the existing body of knowledge primarily consists of port studies but there are a few papers that study vessels. Several researchers integrated their SD model with other models and conducted sensitivity analysis and scenario analysis to confirm the validity of their SD modeling, Moreover, the literature review shows that the MTSSD literature primarily face data-related and complexity-related modeling challenges.

This literature review is an initial step in understanding and demonstrating the causal relations between the different components of the MTS. In the future, a SD model will be built in order to further study the behavior of the MTS and understand the impacts on the major elements of MTS performance. This will help with decision-making strategies that will be beneficial for MTS stakeholders and can result in a competitive advantage for policy makers.

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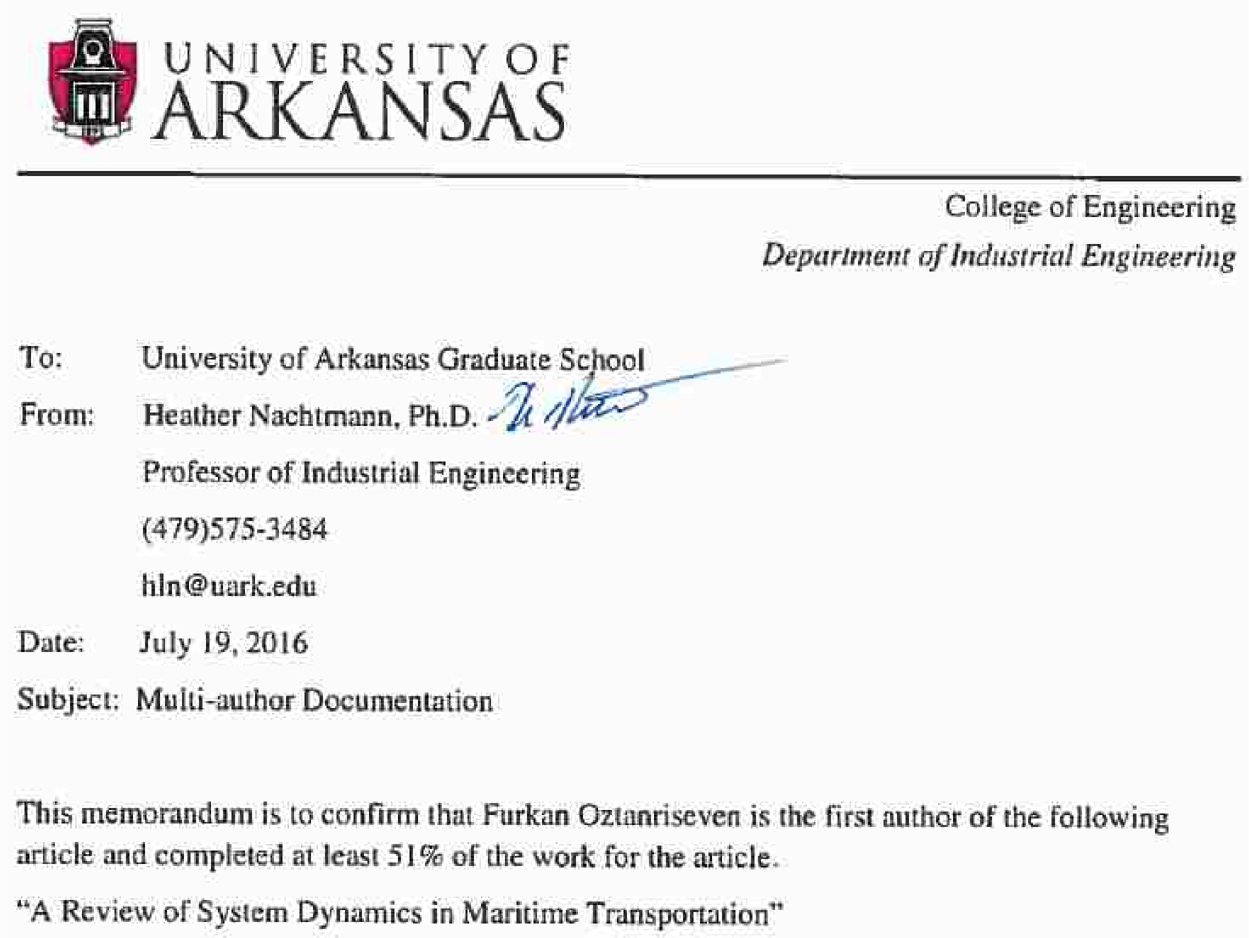
Appendix 1



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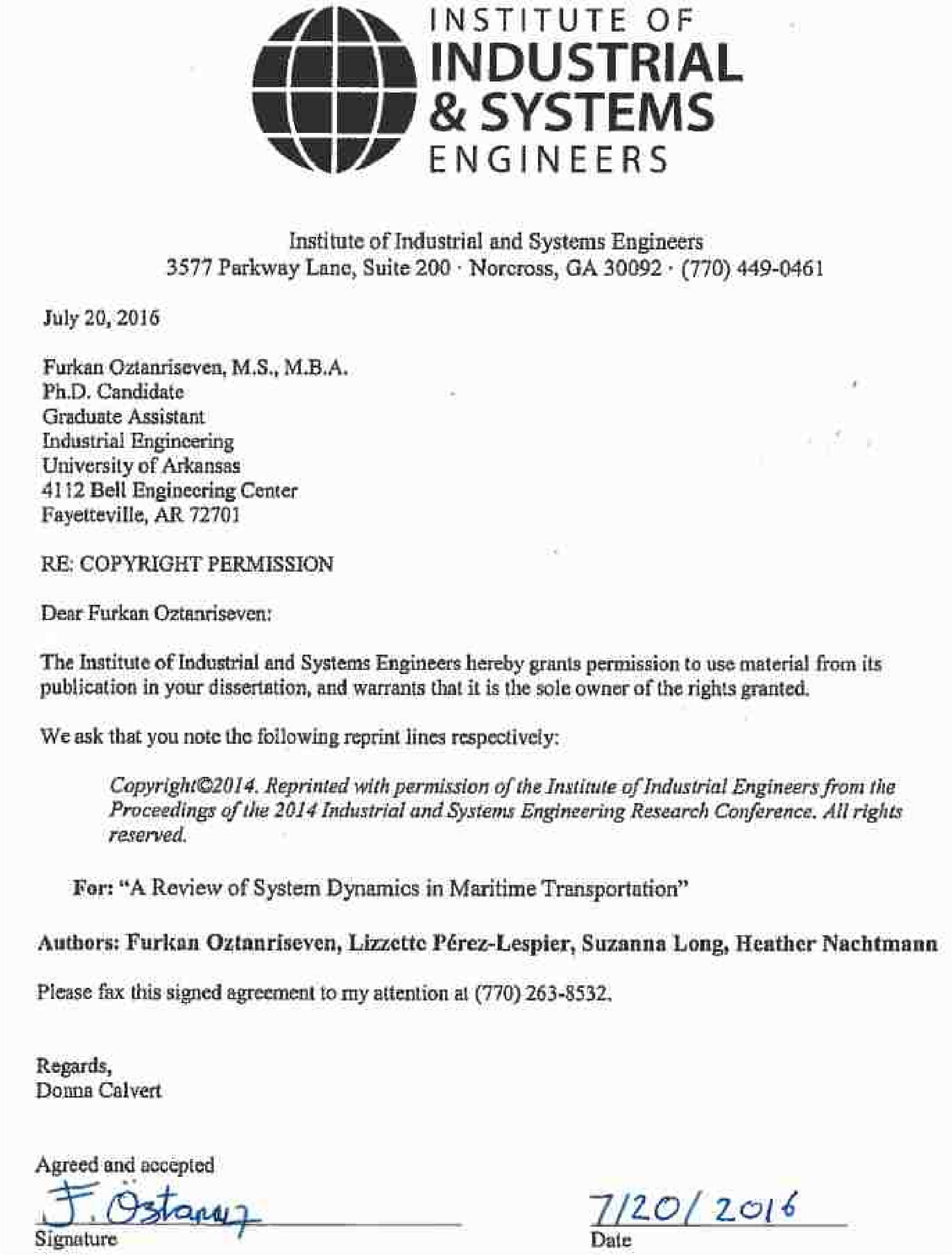
Appendix 2



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3. ECONOMIC IMPACT ANALYSIS OF INLAND WATERWAY DISRUPTION RESPONSE [3]

Abstract

Navigable inland waterways connect inland ports with the global supply chain by providing a low-cost, reliable, and environmentally friendly freight transportation mode. In this paper, we present the results from a simulation-based approach that estimates the potential economic impacts of inland waterway disruption response. Predicting economic impacts of inland waterway disruption response enables system stakeholders to increase their preparedness and potentially reduce economic losses. Our approach is implemented on an illustrative case study of the McClellan-Kerr Arkansas River Navigation System. The approach is generalizable to navigable inland waterways throughout the United States to support economic resilience of these systems.

Keywords: Economic impact analysis, disruption analysis, freight transportation, maritime transportation, inland waterways, Monte Carlo simulation

3.1 Introduction

Navigable inland waterways connect 38 states in the United States. In 2011, a total of $1.7 trillion worth of freight was exported from and imported to U.S. ports (Chambers and Liu, 2012). Navigable inland waterways not only empower economic activities but also provide other benefits such as lower emissions, navigation, water supply, fish and wildlife habitats, recreation, hydropower generation, and flood control (ODOT, 2012).

In terms of transportation benefits, using navigable inland waterways to transport freight is less expensive than transporting by rail or truck. The cost of one ton-mile (moving one ton of

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[3] Published in *the Engineering Economist Journal* (Oztanriseven & Nachtmann, 2016)

freight one mile) is 0.72 cents by barge, 2.24 cents by rail, and 26.62 cents by truck (Guler, et al., 2012). Navigable inland waterways are also more fuel efficient than other modes of transportation (USACE, 2009). One gallon of fuel can move one ton of freight 616 miles by barge, 478 miles by rail, and 150 miles by truck (American Waterways Operators, 2013). Another key advantage of navigable inland waterways is cargo capacity; one barge generally carries 1,750 tons, which is equivalent to the capacity of 16 railcars or 70 tractor trailers (Kruse, et al., 2012). One barge towing vessel typically pushes nine to fifteen barges at a time.

Transporting freight via inland waterways results in fewer fatalities than shipping via railroads or highways. One freight transportation injury occurring on the inland waterways is equivalent to 95 injuries occurring on railroads and as many as 1,610 injuries occurring in truck accidents (Kruse, et al., 2012). In addition, using navigable inland waterways to transport freight relieves already congested roads and railroads. The current usage of inland waterways avoids over 51 million truck trips per year (ASCE, 2013).

We developed a simulation-based approach to investigate the economic impacts of navigable inland waterways disruption response. Our research objective is to better understand the impacts of disruption duration, estimation, and commodity type on economic impact factors. Our approach measures the total economic loss due to a disruption response based on shippers' decisions whether to wait for the inland waterway to reopen or to transfer cargo to an alternative mode of transportation. This decision is evaluated on the expected total cost comprised of transportation cost, holding cost, and penalty cost for both decision alternatives (wait or alternative mode transfer). Based on the shippers' decisions, our model measures the total economic loss for the given disruption scenario. Our approach is implemented on a case study of the McClellan-Kerr Arkansas River Navigation System (MKARNS) to illustrate the economic impacts of disruption response related to this waterway.

3.2 Literature Review

Economic impacts of maritime transportation disruptions and specifically navigable inland waterways have received limited attention in the literature. This literature is summarized in Table 1 and detailed in Oztanriseven and Nachtmann (2013). Prior research has focused primarily on specific types of disruptions, such as natural disasters and man-made failures. For example, the impacts of an earthquake in the New Madrid Seismic Zone on nine Midwestern states and the rest of the United States was studied by Okuyama, et al. (1999). Another example is Olsen, et al. (2005) who measured the benefits of barge services based on commodity price differences in different geographical regions and considered hydrologic variability, such as low flow, flood, and ice, as disruption types. Terrorist attacks and low, medium, and high radioactivity scenarios were studied for the Los Angeles and Long Beach ports by Rosoff and Winterfeldt (2007) who utilized different risk analysis tools including scenario generation and project risk analysis. Lewis, et al. (2006) studied sea port closure and reopening probabilities to measure the productivity impacts of a seaport through a Markov decision model aims to find the optimal inventory management policy.

MacKenzie, et al. (2012) developed a simulation and multiregional input-output framework to measure the economic impact of suddenly closing the inland waterway Port of Catoosa. The primary differences between our work and theirs are: 1) we examine the economic impacts of disruption duration estimation accuracy, 2) we study disruption response strategy by commodity type under various disruption duration scenarios, and 3) we assume that an alternative mode transfer may result in an adverse economic impact. Pant, et al. (2015) also proposed a framework to measure the economic impacts of waterway network disruptions on the Port of Catoosa through the application of dynamic multi-regional interdependency model indicating a total loss over $180 million. Recently, Thekdi and Santos (2015) studied sudden-onset disruptions by implementing interdependency modeling and scenario analysis on the Port of Virginia at Hampton Roads for various disruption scenarios.

Table 1 Types of disruption studied. (Oztanriseven and Nachtmann, 2013)

Type of Disruption	Detail	Author(s)
Natural Disaster	Earthquake	Okuyama (1999)
	Erosion	Richardson and Scott (2004)
Man-made	Labor Strike	Jung, et al. (2009)
	Lockout	Park, et al. (2008)
	Terrorist Attacks	Gordon, et al. (2005)
		Gordon, et al. (2008)
		Rosoff and Winterfeldt
General	▨	Chatterjee, et al. (2001)
		Figliozzi and Zhang (2009)
		Folga, et al. (2009)
		Jones, et al. (2011)
		Kruse, et al. (2011)
		Lewis, et al. (2006)
		Loren C. Scott & Associates
		Pant, et al. (2015)
		Qu and Meng (2012)
		Wang and Miller (1995)
Other	Sudden Port Closures	MacKenzie, et al. (2012)
		Thekdi and Santos (2015)
	Process Disruptions of Ports	Pant, et al. (2011)

Economic impact of maritime transportation disruption research is based on different disruption durations, defined in this study as short-term (10 days), medium-term (60 days), and long-term (180 days). Recent real world examples of short-term disruptions are ten day lockout of Los Angeles/Long Beach ports (Khouri, 2015), ten day closure due to Montgomery Lock and Dam failure (Guler, et al., 2012), eleven day of disruption due to McAlpine Lock repair (Harris, 2004), twelve day port network shutdown (Gerencser, et al., 2003), and ten day port closure of West Coast ports (Martin Associates, 2001). Medium-term real world disruption examples include fifty-two day of closure in 2003 due to Greenup Lock and Dam failure and maintenance (Guler, et al., 2012), two months of disruption due to Interstate 40 bridge collapse across the Arkansas River (Volpe, 2008), and one month disruption of Los Angeles/Long Beach Ports (Park, et al., 2005; Rosoff and Winterfeldt, 2007). Example of related long-term disruptions studied in the literature are 120 day to 365 day shutdown of Los Angeles/Long Beach Ports due to a terrorist attack (Rosoff & Winterfeldt, 2007) and 120 day of disruption due to a dirty bomb attack to Los Angeles/Long Beach Ports (Gordon, et al., 2005). Although each disruption has unique characteristics, research shows the severity in terms of economic impacts due to disruptions. For example, a one-month closure of the Ports of Los Angeles/Long Beach, New York-New Jersey and Houston may lead to negative economic impacts of approximately $21 billion, $14.4 billion and $8.4 billion respectively (Park, et al., 2005).

Our review of the relevant literature indicates that there is lack of decision support tools that do not require primary data collection for water transportation authorities to develop disruption mitigation policies for potential navigable inland waterway disruptions. This primary data collection is very costly in terms of time and resources. In addition, our review indicates that there is no published research that examines the economic importance of disruption duration estimation accuracy related to maritime disruption response. The simulation-based approach presented in this paper examines the economic impacts of disruption duration, estimation, and commodity type on inland waterway disruption response.

3.3 Methodology

3.3.1 Disruption Scenarios

To assess the economic impacts of navigable inland waterway disruptions, we developed a Monte-Carlo simulation model to assess economic impacts under various disruption scenarios including multiple disruption durations, estimation accuracy levels, commodity types.

We define disruption durations as short-term (10 days), medium-term (60 days), and long-term (180 days) durations based on disruption durations studied in the literature and real disruption cases as discussed in the literature review. For each scenario, there are two decision alternatives: 1) wait for the waterway to reopen and remain on the waterway or 2) transfer cargo to an alternative mode of transportation. Each scenario considers three possible disruption duration estimation outcomes; accurate estimation (A.E.), overestimation (O.E.), and underestimation (U.E.). In accurate estimation, the duration of disruption is accurately estimated. In the overestimation and underestimation cases, the estimated disruption duration is not accurately under three possible estimation error levels (10%, 20%, and 30%). The model considers commodities typically transported on the inland waterways including iron and steel, chemical fertilizer, petroleum products, coal and coke, sand, gravel, and rock, soybeans, wheat, other grains, forest products/minerals, and manufactured equipment and machinery.

Results of our study provide information to support strategic investment in future navigable inland waterway infrastructure development. This can increase the competitive advantage of the associated region, while benefiting from the environmental and societal advantages associated with the maritime transportation mode.

3.3.2 Model Assumptions

Model assumptions related to the behavior of the system are summarized in Table 2.

Table 2 Assumptions

Assumptions	**Reference**
No capacity constraint on alternative modes of transportation	MacKenzie, et al. (2011)
The market behaves monopolistically, so there are no substitutes for commodities	Thissen (2004)
Annual holding cost rate of 24.33%	Lewis, et al. (2006)
Penalty cost rate of 3% for the first week of delay and 10% for the other weeks	Kwon, et al. (1998)
Transportation cost is 0.72 cents for barge, 2.24 cents for rail, and 26.61 cents for truck per ton mile	Guler, et al. (2012)
As soon as the disruption is over, all barges that queued up will be able to move immediately	Pant, et al. (2011)

After formulating the underlying assumptions and parameter estimates, the total disruption cost is calculated as the sum of three cost components - holding cost, penalty cost, and transportation cost.

3.3.3 Model Formulation

In this section, the model formulation of our simulation-based approach is presented, including the sets, parameters, and equations. The purpose of our model is to measure total economic loss due to inland waterway disruption response. Total economic loss is defined as the sum of holding cost, penalty cost, and transportation cost. To compute these costs, we calculate the number of commodity shipments per day, average travel distance, and average value of commodity. The notation and formulation of our economic impacts of inland waterway disruption decision model are as follows:

Sets	
$i \epsilon I$	Set of commodities
$t \epsilon T$	Set of years
$k \epsilon K$	Set of flow types *k* = {1: inbound, 2: outbound, 3: internal, 4: through}
$l,m,n \epsilon L$	Set of regions located in the study region
$j,j' \epsilon S_l$	Set of port locations (river mile) in state *l*
$q \epsilon Q$	Set of transportation modes *q* = {1: water, 2: rail, 3: truck, 4: other}
Parameters	
$f_i^q(t)$	Flow of commodity *i* by mode of transportation *q* in year t
B_i	Capacity of a barge carrying commodity *i*
N_i	Number of barges per shipment of commodity *i*
$\Theta(t)$	Number of working days without a disruption in year *t*
$\Lambda_i(t)$	Average number of commodity *i* shipments per day in year *t*
$w_j(t)$	Flow weight of port that is located at *j* in year *t*
$d_{jj'}$	Distance (river mile) between ports *j* and *j'*
g_l^k	Commodity flow from state *l* by type *k*
$\overline{d_k}(t)$	Average travel distance for flow type *k* in year *t*
$\bar{d}(t)$	Average travel distance in the study region in year *t*
$u_q(t)$	Normalized usage rate of q^{th} mode of transportation in year *t*
$\overline{\alpha_i}(t)$	Average value of commodity *i* per ton in year *t*
$\overline{v_i}(t)$	Average value of commodity *i* per shipment in year *t*
$\varphi_q(t)$	Transportation cost rate of transportation mode *q* per ton mile in year *t*
Δt_i^q	Commodity *i* transportation mode *q* number of delivery days delay due to a disruption
$E(\Delta t_i^q)$	Expected number of delivery days delay for commodity *i* transportation mode *q* at the beginning of a disruption
$p_i(t, \Delta t_i^q)$	Commodity *i* penalty cost rate per day due to Δt_i^q days of delay in year *t*
$h_i(t, \Delta t_i^q)$	Commodity *i* holding cost rate per day due to Δt_i^q days of delay in year *t*
$\Phi_i^q(t)$	Commodity *i* transportation cost rate per shipment for transportation mode *q* in year *t*
$P_i(t, \Delta t_i^q)$	Commodity *i* penalty cost rate per shipment per day due to Δt_i^q days of delay in year *t*
$H_i(t, \Delta t_i^q)$	Commodity *i* holding cost rate per shipment per day due to Δt_i^q days of delay in year *t*
$\Delta C_i(t, \Delta t_i^q, E[\Delta t_i^q])$	Commodity *i* economic loss per shipment due to a disruption that cause Δt_i^q days of delivery delay when the expected delivery delay is $E[\Delta t_i^q]$ in year *t*
$C(t, \Delta t_i^q, E[\Delta t_i^q])$	Total economic loss per shipment due to a disruption that cause Δt_i^q days of delivery delay when the expected delivery delay is $E[\Delta t_i^q]$ in year *t*

Model

$$\mathit{\Lambda}_i(t) = \left(\frac{f_i^1(t)}{B_i N_i \mathit{\Theta}(t)}\right) \quad \forall i \epsilon \mathrm{I}; \forall \mathrm{t} \epsilon \mathrm{T} \tag{1}$$

$$\overline{d_1}(t) = \overline{d_2}(t) = \begin{cases} \displaystyle\sum_{j \epsilon S_l} \sum_{j' \notin S_L} \left(\frac{w_j(t) w_{j'}(t)}{\sum_{j \epsilon S_l} \sum_{j' \notin S_L} w_j(t) w_{j'}(t)} d_{j max\{S_L\}} \right) & \forall l \epsilon \mathrm{L}; \forall \mathrm{t} \epsilon \mathrm{T}; \mathrm{j} < j' \\ \displaystyle\sum_{j \epsilon S_l} \sum_{j' \notin S_L} \left(\frac{w_j(t) w_{j'}(t)}{\sum_{j \epsilon S_l} \sum_{j' \notin S_L} w_j(t) w_{j'}(t)} d_{j min\{S_L\}} \right) & \forall l \epsilon \mathrm{L}; \forall \mathrm{t} \epsilon \mathrm{T}; \mathrm{j} > j' \end{cases} \tag{2}$$

$$\overline{d_3}(t) = \sum_{j \epsilon S_l} \sum_{j' \epsilon S_l} \left(\frac{w_j(t) w_{j'}(t)}{\sum_{j \epsilon S_l} \sum_{j' \epsilon S_l} w_j(t) w_{j'}(t)} d_{jj'} \right) \quad \forall l \epsilon \mathrm{L}; \forall \mathrm{t} \epsilon \mathrm{T}; \mathrm{j} < j' \tag{3}$$

$$\overline{d_4}(t) = \sum_{j \notin S_L} \sum_{j' \notin S_L} \left(\frac{w_j(t) w_{j'}(t)}{\sum_{j \notin S_L} \sum_{j' \notin S_L} w_j(t) w_{j'}(t)} d_{min\{S_L\} max\{S_L\}} \right) \quad j' > max\{S_L\}; \mathrm{j} < min\{S_L\}; \forall \mathrm{t} \epsilon \mathrm{T} \tag{4}$$

$$\bar{d}(t) = \frac{\sum_{l \epsilon \mathrm{L}} \sum_{k=1}^{2} g_l^k \left(\overline{d_1}(t) + \overline{d_2}(t) \right) + \sum_{l \epsilon \mathrm{L}} g_l^3 \overline{d_3}(t) + \sum_{l \epsilon \mathrm{L}} g_l^4 \overline{d_4}(t)}{\sum_{l \epsilon \mathrm{L}} \sum_{k=1}^{4} g_l^k} \tag{5}$$

$$\overline{v_\iota}(t) = \overline{\alpha_\iota}(t) B_i N_i \quad \forall i \epsilon \mathrm{I}; \forall \mathrm{t} \epsilon \mathrm{T} \tag{6}$$

$$\mathit{\Phi}_i^q(t) = \varphi_q(t) \bar{d}(t) B_i N_i \quad \forall i \epsilon \mathrm{I}; \forall \mathrm{t} \epsilon \mathrm{T}; \ \forall q \epsilon \mathrm{Q} \tag{7}$$

$$P_i(t, \mathit{\Delta} t_i^q) = p_i(t, \mathit{\Delta} t_i^q) \overline{v_\iota} \, \mathit{\Delta} t_i^q \quad \forall i \epsilon \mathrm{I}; \forall \mathrm{t} \epsilon \mathrm{T}; \forall q \epsilon \mathrm{Q} \tag{8}$$

$$H_i\left(t, \mathit{\Delta} t_i^q\right) = h_i\left(t, \mathit{\Delta} t_i^q\right) \overline{v_\iota} \, \mathit{\Delta} t_i^q \quad \forall i \epsilon \mathrm{I}; \forall \mathrm{t} \epsilon \mathrm{T}; \forall q \epsilon \mathrm{Q} \tag{9}$$

$$\begin{aligned} &\mathit{\Delta} C_i(t, \mathit{\Delta} t_i^q, E[\mathit{\Delta} t_i^q]) \\ &= \begin{cases} \left(P_i(t, \mathit{\Delta} t_i^1) + H_i(t, \mathit{\Delta} t_i^1) \right) & \forall i \epsilon \mathrm{I}; \forall \mathrm{t} \epsilon \mathrm{T}; \mathit{\Delta} C_i(t, \mathit{\Delta} t_i^1, E[\mathit{\Delta} t_i^1]) \leq z = \displaystyle\sum_{q \epsilon \mathrm{Q}} u_q(t) \mathit{\Delta} C_i(t, \mathit{\Delta} t_i^q E[\mathit{\Delta} t_i^q] \\ \displaystyle\sum_{\forall q \neq 1} u_q(t) \left(\mathit{\Phi}_i^q(t) - \mathit{\Phi}_i^1(t) + P_i\left(t, \mathit{\Delta} t_i^q\right) + H_i\left(t, \mathit{\Delta} t_i^q\right) \right) & \forall i \epsilon \mathrm{I}; \forall \mathrm{t} \epsilon \mathrm{T}; \mathit{\Delta} C_i(t, \mathit{\Delta} t_i^1, E[\mathit{\Delta} t_i^1]) \geq z \end{cases} \end{aligned} \tag{10}$$

$$C(t, \mathit{\Delta} t_i^q, E[\mathit{\Delta} t_i^q]) = \sum_{i \epsilon \mathrm{I}} \mathit{\Delta} C_i(t, \mathit{\Delta} t_i^q, E[\mathit{\Delta} t_i^q]) \mathit{\Lambda}_i(t) \quad \forall \mathrm{t} \epsilon \mathrm{T}; \ \forall q \epsilon \mathrm{Q} \tag{11}$$

The model formulation represents navigable inland waterways in a given study region during year *t*. Equation (1) calculates the average number of shipments per day needed to accommodate the commodity *i* by dividing the flow of commodity by shipment capacity by the number of working days without disruption. Equation (2) calculates the expected travel distance for inbound and outbound freight flow by multiplying the distance between the ports in the region *l* with the ports that are not located in the study region by a port weight factor. A port weight is calculated to estimate the commodity flows between different ports to estimate the average travel distance $\bar{d}(t)$. The reason for this estimation is the unavailability of data for the commodity flow values between individual ports. Therefore, port flow weights are obtained from water transportation authorities to calculate these port weight factors. Similarly, port weight factors are utilized for internal and through traffic flows in Equations (3) and (4) respectively. The average travel distance in the study region is calculated in Equation (5) by the weighted sum of the average flow distances calculated in Equations (2)-(4). The weights in Equation (5) are calculated by dividing commodity flow by flow type by total commodity flow of all flow types. Equation (6) calculates the average value of commodity *i* per shipment by multiplying the average value of commodity per ton by shipment capacity. Equations (7)-(9) calculate transportation, penalty, and holding costs respectively. However, it is important to note that the penalty cost rate, $p_i(t, \Delta t_i^q)$, and holding cost rate, $h_i(t, \Delta t_i^q)$, are functions of commodity type, time, deliver days delay of commodity *i* for transportation mode q due to a disruption whereas transportation cost rate, $\varphi_w(t)$, is a function of ton mile in year *t* for transportation mode q. Equation (10) calculates how much additional cost is incurred per shipment for each commodity type due to a disruption scenario. Finally, Equation (11) calculates the total economic loss due to a potential disruption for all commodities in the study region in a given year.

3.4 Case Study: McClellan-Kerr Arkansas River Navigation System Overview

To demonstrate our approach, we implement our methodology on the MKARNS. The MKARNS, as shown in Figure 1, connects the heartland of the United States with the rest of the world via Mississippi River and the Port of New Orleans.

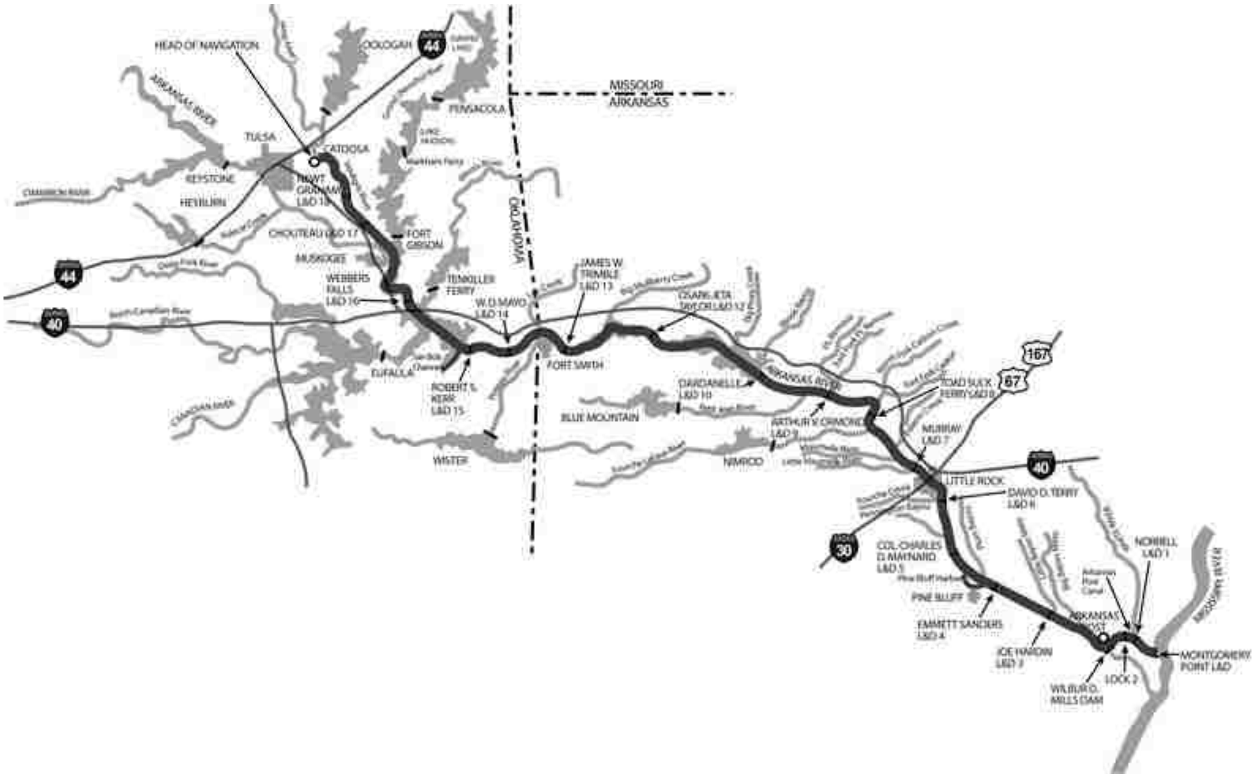


Figure 1 MKARNS Map (USACE, n.d.).

The MKARNS consists of the Verdigris River, Arkansas River, and White River (ODOT, 2012). Thirteen of its eighteen locks are located in Arkansas, and five of its locks are located in Oklahoma (AOPOA, 2010). The locks on the MKARNS are 600-feet long and 110-feet wide allowing for eight barges and one towboat to be contained within each lockage (ODOT, 2015). In 2014, 11.7 million tons of freight was transported via the MKARNS (ODOT, 2015). These goods include iron and steel, chemical fertilizer, petroleum products, coal and coke, sand, gravel, and rock, soybeans, wheat, other grains, forest products/minerals, and manufactured equipment and machinery (ODOT, 2015). Another important fact about the MKARNS is that it offers yearround accessible inland waterways through five public ports and approximately fifty private terminals (AOPOA, 2013).

3.4.1 Data Used

We limited our case study to publically available data which was validated by three subject matter experts including a waterways manager of a State Department of Transportation, a United States Army Corps of Engineers (USACE) regional economist, and an executive director of a State Waterways Organization.

The parameter values and the corresponding sources are illustrated in Table 3. Also, the consumer price index is utilized to adjust the data to 2013 dollars.

Table 3 Data Sources

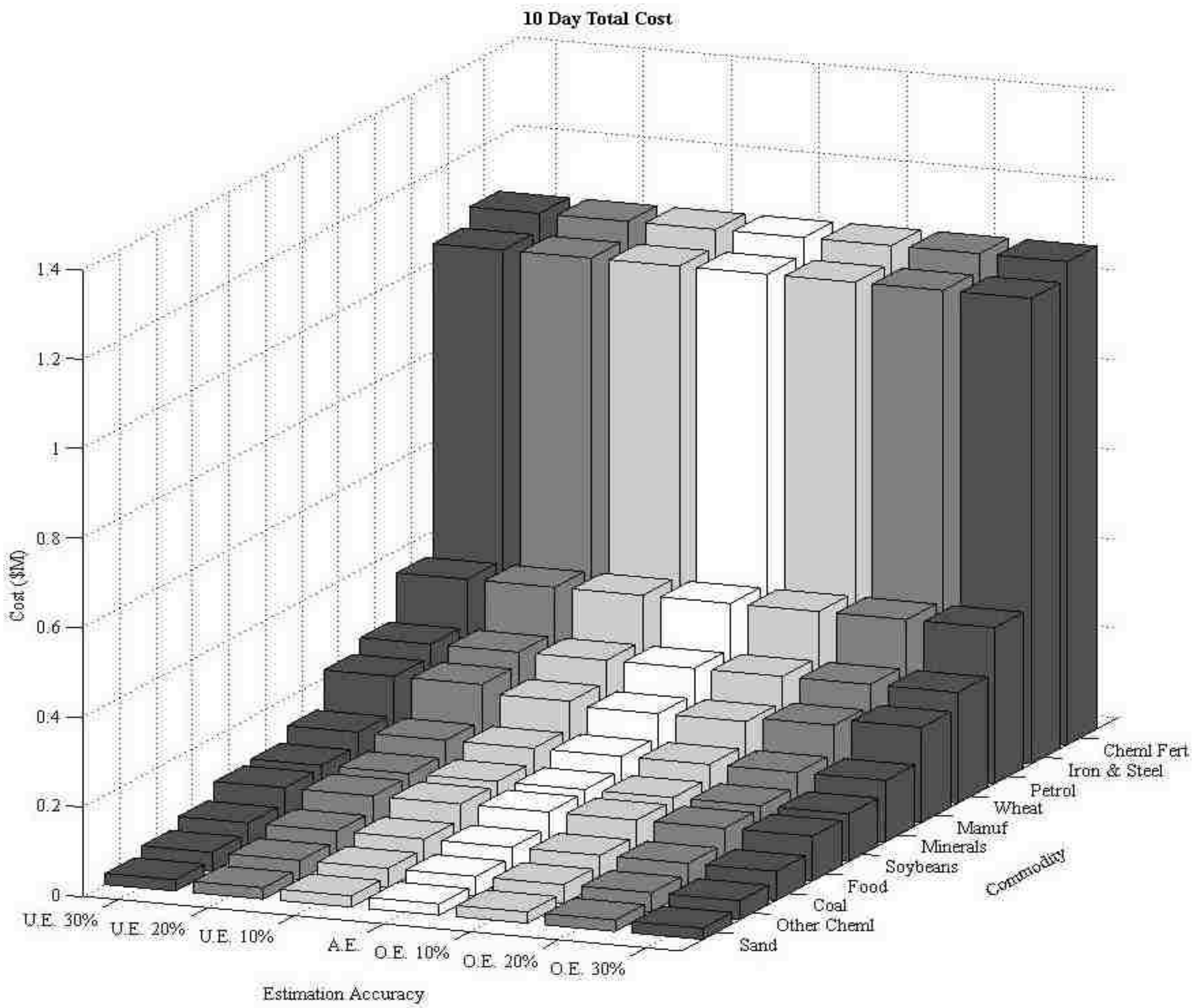
Description	Parameter	Source
Commodity flow	$f_i^p(t), g_l^k$	USACE (2014)
Barge capacity	$B_i \sim Tri(1400{,}1450{,}1500)$	IDOT (2008)
# of barges per shipment	$N_i \sim Tri(6{,}8{,}17)$	Arkansas Waterways Commission (2011)
# of working days in a year	$\Theta(t)$=365 days in a year	AOPOA (2012)
Port weight factor	$w_j(t)$	Arkansas Waterways Commission (2011)
Mode q usage rate	$u_q(t)$	USDOT (2010)
Commodity value	$\overline{\alpha}_\iota(t)$	AOPOA (2012)
Transportation cost rate	$\varphi_w(t)$	Guler, et al. (2012)
Penalty cost rate	$p_i(t, \Delta t_i^q) = \begin{cases} 0.006\ \overline{\alpha}_\iota(t) & , \Delta t_i^q < 1\ week \\ 0.014 * \overline{\alpha}_\iota(t) & , \Delta t_i^q > 1\ week \end{cases}$	Painter and Whalen (2010)
Holding cost rate	$h_i(t, \Delta t_i^q)$=0.0007 $\overline{\alpha}_\iota(t)$	Lewis, et al. (2006)

3.4.2 Analysis

We ran our simulation model for three different disruption durations: short-term, medium-term, and long-term. We utilized @RISK 6 software to run our Monte Carlo simulation for 5,000 iterations for each disruption scenario.

3.4.3 Results

Some general findings were observed from our case study. As expected, providing an accurate estimation of the disruption duration leads to the lowest total disruption cost. Underestimating the disruption duration by 30% results in the highest total disruption cost for all three disruption duration scenarios. Furthermore, the *iron and steel* (Iron & Steel) and *chemical fertilizer* (Cheml Fert) commodities always cause the majority of the total disruption cost. In the short-term, medium-term, and long-term scenarios, these two commodities account for 62%, 50%, and 46% of the total disruption cost respectively. However, each disruption duration scenario has also its own distinct findings which are discussed next.

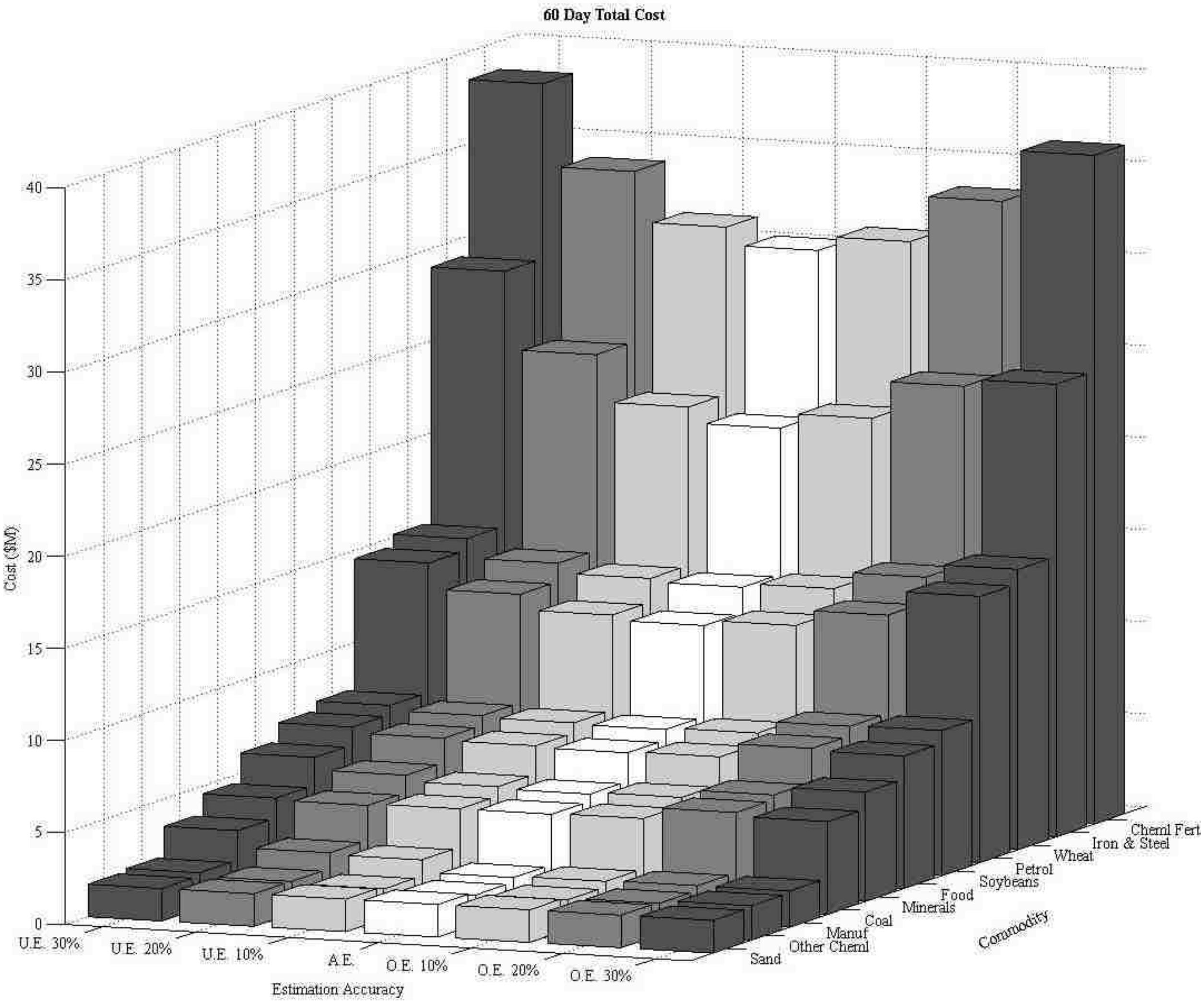


10 Day Disruption Total Cost by Commodity ($M)

Estimation Accuracy		Cheml Fert	Iron & Steel	Petrol	Wheat	Manuf	Minerals	Soybeans	Food	Coal	Other Cheml	Sand	Total
Under Estimation	-30%	$ 1.08	$ 1.04	$0.35	$0.25	$0.22	$ 0.14	$ 0.11	$0.10	$0.06	$ 0.04	$0.03	$3.41
	-20%	$ 1.08	$ 1.04	$0.35	$0.25	$0.22	$ 0.14	$ 0.11	$0.10	$0.06	$ 0.04	$0.03	$3.41
	-10%	$ 1.08	$ 1.04	$0.35	$0.25	$0.20	$ 0.14	$ 0.11	$0.10	$0.06	$ 0.04	$0.03	$3.39
Accurate Estimation	100%	$ 1.08	$ 1.04	$0.35	$0.25	$0.19	$ 0.14	$ 0.11	$0.10	$0.06	$ 0.04	$0.03	$3.38
Over Estimation	10%	$ 1.08	$ 1.04	$0.35	$0.25	$0.19	$ 0.14	$ 0.11	$0.10	$0.06	$ 0.04	$0.03	$3.38
	20%	$ 1.08	$ 1.04	$0.35	$0.25	$0.20	$ 0.14	$ 0.11	$0.10	$0.06	$ 0.04	$0.03	$3.39
	30%	$ 1.08	$ 1.04	$0.35	$0.25	$0.21	$ 0.14	$ 0.11	$0.10	$0.06	$ 0.04	$0.03	$3.40

Figure 2 Total Disruption Cost Results for Short-term Disruption Scenario by Commodity and Estimation Accuracy

Figure 2 summarizes the expected values of the total disruption cost for the short-term disruption scenario by commodity and estimation accuracy. Overall, the results of the short-term disruption scenario indicate that underestimating the disruption duration leads to slightly higher total disruption cost (due to m*anufactured equipment and machinery*) than the corresponding overestimations. For example, 30% underestimation results in a total disruption cost of $3.41 million where 30% overestimation leads to $3.40 million in total disruption cost. The main cost component (88%) contributing to the total disruption cost is penalty cost. Additionally, the total cost graph in Figure 2 appears to be relatively flat. In general, all commodities, except *manufactured equipment and machinery*, incur the same total disruption cost across all estimation accuracy levels. *Manufactured equipment and machinery* ($5,000 per ton) is a highly valuable commodity in comparison to the other commodity types, for example, *sand/gravel and rock (Sand)* is valued at $10 per ton. Thus, for companies transporting *manufactured equipment and machinery*, their penalty cost and holding cost will be greater since these two cost types are assessed based on a percentage of commodity value. The results show that, even for short-term disruptions, the *manufactured equipment and machinery* commodity should be transported by an alternative mode instead of waiting for the inland waterway to reopen in order to minimize the total disruption cost incurred.



60 Day Disruption Total Cost by Commodity ($M)

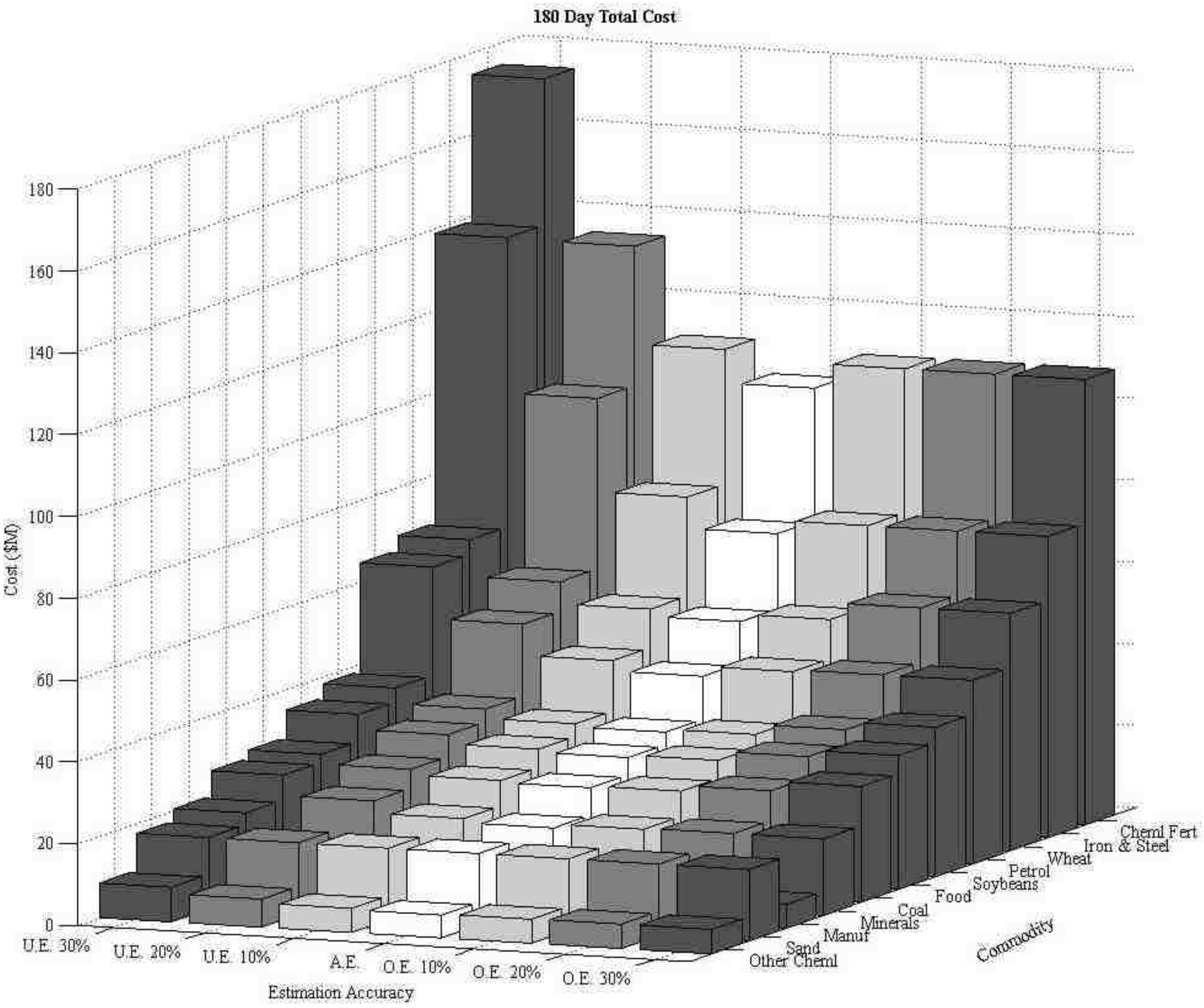
Estimation Accuracy		Cheml Fert	Iron & Steel	Wheat	Petrol	Soybeans	Food	Minerals	Coal	Manuf	Other Cheml	Sand	Total
	-30%	$ 38.42	$ 28.94	$15.14	$14.52	$ 7.50	$7.02	$ 6.07	$4.56	$3.50	$ 1.91	$1.77	$129.36
Under Estimation	**-20%**	$ 33.95	$ 24.71	$14.10	$13.12	$ 7.23	$6.71	$ 5.40	$4.46	$2.59	$ 1.73	$1.77	$115.76
	-10%	$ 31.23	$ 22.17	$13.57	$12.28	$ 7.13	$6.59	$ 5.07	$4.56	$2.49	$ 1.62	$1.77	$108.46
Accurate Estimation	**100%**	$ 30.25	$ 21.31	$13.38	$12.00	$ 7.06	$6.49	$ 4.96	$4.56	$1.83	$ 1.58	$1.77	$105.18
	10%	$ 31.02	$ 22.13	$13.59	$12.29	$ 7.16	$6.57	$ 5.07	$4.62	$1.91	$ 1.61	$1.77	$107.72
Over Estimation	**20%**	$ 33.50	$ 24.17	$14.50	$13.14	$ 7.81	$7.31	$ 5.49	$5.24	$1.96	$ 1.71	$1.77	$116.60
	30%	$ 36.29	$ 24.56	$15.22	$14.45	$ 7.87	$7.19	$ 5.93	$5.03	$1.96	$ 1.87	$1.77	$122.15

Figure 3 Total Disruption Cost Results for Medium-term Disruption Scenario by Commodity and Estimation Accuracy

Achieving higher estimation accuracy gains more importance as the disruption duration increases. Whereas the total disruption cost impact was relatively flat in the short-term disruption scenario, Figure 3 illustrates that underestimating or overestimating the disruption duration for medium-term disruption scenario leads to a relatively greater increase in total disruption cost.

For the medium-term disruption duration, it cannot be clearly identified whether over- or under-estimating the disruption duration leads to lower total disruption cost. However, looking at the individual commodities provides further insights. For instance with the *coal and coke, wheat*, and *soybeans* commodities, underestimating the disruption duration leads to lower total disruption cost than overestimating the disruption duration. However, for the *iron and steel, chemical fertilizer,* and *other chemicals (Other Cheml)* commodities, the opposite is observed where overestimating the disruption duration leads to lower total disruption cost in comparison to underestimating it. For the medium-term disruption scenario, penalty cost and transportation cost are the major disruption cost components. As outlined in Figure 3, when the disruption duration is overestimated, more commodities are transported via alternatives modes and therefore lead to increased transportation cost. Figure 3 highlights in grey the scenarios where transportation cost is the largest cost component. Similarly, non-highlighted cells in Figure 3 represent scenarios in which penalty cost is the largest cost component.

Furthermore, Figure 3 illustrates how the total disruption cost of commodities is impacted differently by estimation accuracy. For *sand/gravel and rock*, there is no change in total disruption cost based on the estimation accuracy. *Manufactured equipment and machinery* experiences a 92% increase in disruption cost from accurate estimation to the 30% underestimation scenario. Other commodities experience an increase up to 36% with an average increase of 20%.



180 Day Disruption Total Cost by Commodity ($M)

Estimation Accuracy		**Cheml Fert**	**Iron & Steel**	**Wheat**	**Petrol**	**Soybeans**	**Food**	**Coal**	**Minerals**	**Manuf**	**Sand**	**Other Cheml**	**Total**
	-30%	$ 174.5	$ 138.8	$68.2	$64.7	$ 38.3	$35.0	$28.4	$ 26.4	$20.3	$17.5	$ 8.5	$620.4
Under Estimation	**-20%**	$ 134.9	$ 100.9	$59.2	$52.0	$ 34.4	$31.3	$26.0	$ 21.4	$12.3	$17.5	$ 6.9	$496.7
	-10%	$ 111.0	$ 78.1	$53.8	$44.4	$ 32.1	$29.1	$24.6	$ 18.4	$ 7.4	$17.5	$ 5.9	$422.3
Accurate Estimation	**100%**	$ 102.8	$ 70.4	$52.1	$41.9	$ 31.4	$28.3	$24.1	$ 17.4	$ 5.8	$17.5	$ 5.6	$397.2
	10%	$ 108.9	$ 73.7	$53.9	$44.3	$ 32.1	$28.9	$24.6	$ 18.4	$ 5.9	$17.5	$ 5.9	$414.0
Over Estimation	**20%**	$ 108.9	$ 73.7	$58.0	$44.8	$ 34.6	$31.2	$26.0	$ 18.7	$ 5.9	$17.5	$ 6.0	$425.1
	30%	$ 108.9	$ 73.7	$58.0	$44.8	$ 36.5	$32.7	$28.3	$ 18.7	$ 5.9	$17.5	$ 6.0	$431.0

Figure 4 Total Disruption Cost Results for Long-term Disruption Scenario by Commodity and Estimation Accuracy

The results of the long-term disruption scenario indicate that overestimating the disruption duration always leads to lower total disruption cost than underestimating the disruption duration. In comparison to overestimating the duration by 30% scenario, underestimating the disruption duration by 30% scenario leads to an increase in total disruption cost of $189.4 million.

Similar to the findings for the medium-term disruption scenario, estimation accuracy has no impact on the *sand/gravel and rock* commodity. The results in Figure 4 illustrate that overestimating the disruption duration leads to lower total disruption cost than the corresponding underestimation scenarios for *chemical fertilizer*, *iron and steel*, *petroleum products (Petrol), food products (Food), coal and coke (Coal), minerals, manufactured equipment and machinery (Manuf)*, and *other chemicals*. Similar to the medium-term disruption scenario, the long-term disruption scenario penalty cost and transportation cost are the major cost components. However, transportation cost gains even more importance and constitutes a larger component of the total disruption cost in comparison to the medium-term disruption scenario.

Furthermore, Figure 4 illustrates how the total disruption cost of commodities is impacted differently by estimation accuracy. Similar to the medium-term scenario, there is no change in total disruption cost based on the estimation accuracy level for the *sand/gravel and rock* commodity. *Manufactured equipment and machinery* experiences the highest increase with a 253% disruption cost increase from accurate estimation to the 30% underestimation scenario. All other commodities may only experience an increase up to 96% with an average increase of 47%.

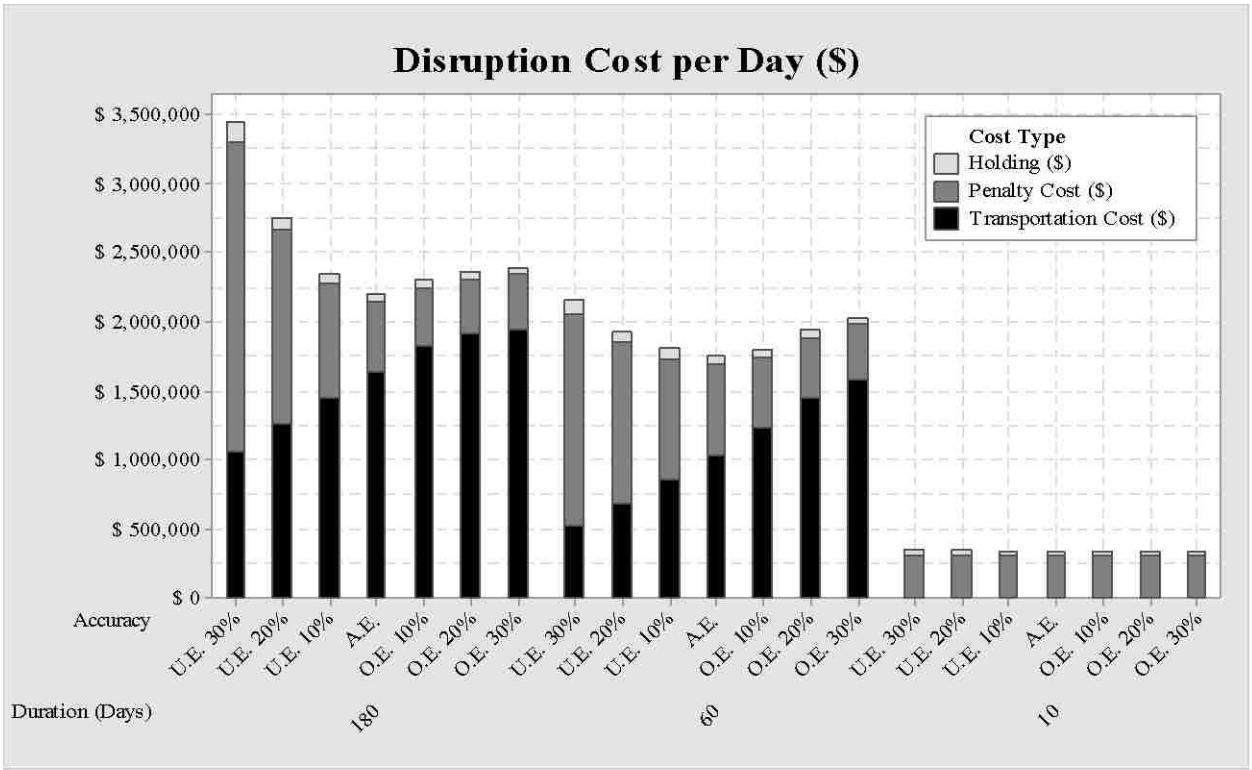


Figure 5 Total Disruption Cost Results per Day by Disruption Accuracy and Duration

Figure 5 illustrates the total disruption cost per day for each of the three scenarios. These results indicate that the total disruption cost per day increases as the disruption duration also increases. However, this relationship does not appear to be linear. For the short-term disruption scenario, transportation cost is almost zero since most commodities will wait for the inland waterway to reopen. When the disruption duration is medium term (60 days) or long-term (180 days), transportation cost is a significant component of the total disruption cost. Furthermore, there is a cost trade-off between penalty and transportation cost. In the medium-term and long-term scenarios, the results show that when underestimation occurs, penalty cost exceeds transportation cost since commodities will wait for the inland waterway to reopen; whereas when overestimation occurs, more commodities will be transported via alternative modes and lead to a higher transportation cost than penalty cost.

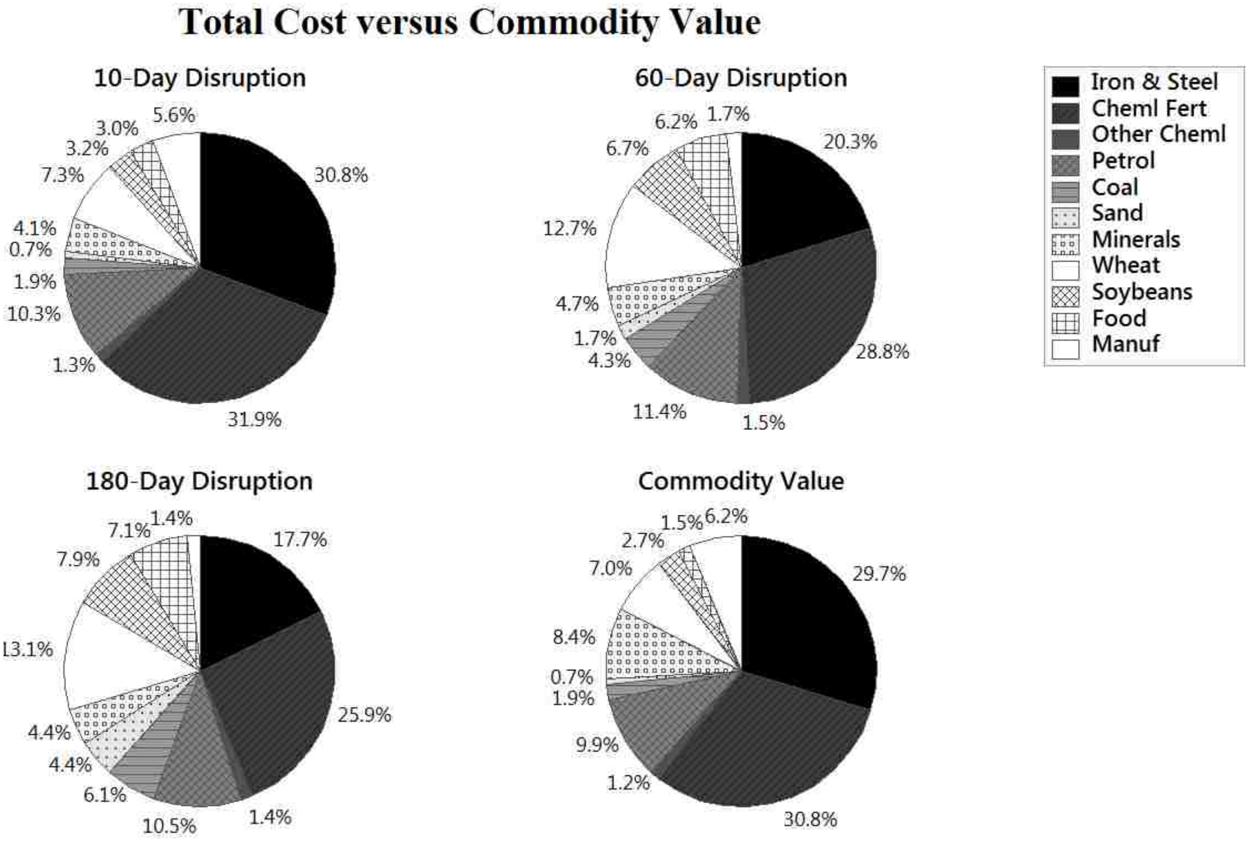


Figure 6 Total Disruption Cost versus Commodity Value for A.E.

Figure 6 summarizes the total disruption cost versus the commodity value for each of the three disruption duration scenarios. These charts illustrate that, depending on the disruption duration, the proportion of total disruption cost caused by a commodity may vary. Therefore, different disruption mitigation policies should be developed by the water transportation authorities. Observing similar distribution charts that show the impact that estimation accuracy level has on the total disruption cost by commodity indicate similar results regardless of the disruption duration. Therefore, we chose the accurate estimation scenarios to represent all other scenarios in Figure 6. The results in Figure 6 show that the relationship between the commodity value and the total disruption cost incurred by a specific commodity are not the same in all three scenarios. For example, while *iron and steel* constitute more than 30% of the total disruption cost in the short-term disruption scenario; in the long-term disruption scenario, this commodity constitutes less than 18% of the total disruption cost. Similarly, the total disruption cost proportions for *chemical fertilizer* and *manufactured equipment and machinery* also decrease for longer disruption durations. On the contrary, the total disruption cost percentage for some other commodities, *coal and coke*, *wheat*, *soybeans*, and *food products*, increase with an increase in disruption duration. For example, the total disruption cost for *coal and coke* increases from 2% in the short-term disruption scenario to 6% in the long-term disruption scenario. Thus, some commodities, *coal and coke, sand, gravel, and rock*, *soybeans, food,* and *manufactured equipment and machinery* seem to be more sensitive to disruption duration than others and warrant managerial attention.

3.4.4 Case Discussion

Our results suggest that estimation of disruption duration plays an important role in transportation decisions, particularly for long-term disruptions. As shown by our case study, increasing disruption duration estimation accuracy may reduce the total disruption cost significantly (25% for medium-term and 61% for long-term disruptions on average). However, it is difficult to predict the length of disruption duration because of the unpredictable nature of disruptions. For instance, while the length of a disruption stemming from a natural disaster or a man-made attack might be difficult to estimate, the length of a planned maintenance activity might be easier to predict based on prior experience. Thus, inland waterways transportation managers may want to carefully consider and analyze historical data from prior disruptions to improve their disruption duration estimation. Additionally, these managers could utilize our model to conduct scenario analysis for highly unpredictable disruptions to develop contingency plans for potential future disruptions.

Primary findings of our MKARNS case study include:

- To reduce the economic impact of a disruption, managers should not only consider the total value of commodity flow in their system but also how each commodity is sensitive to disruption duration and accuracy of estimation. Therefore, when governmental agencies make investment decisions to improve the infrastructure of the navigable inland waterways system (e.g. port handling and access to alternative modes of transportation), it is important to also consider the characteristics of potential future disruptions (e.g. anticipated disruption duration and uncertainty) for more sensitive types of commodities.
- Companies that are expecting more short-term disruptions have several options to mitigate their potential financial loss. For example, companies might be able to negotiate with their customers to lower their penalty cost rates since penalty cost is the main disruption cost component for short-term disruptions. Also, companies might want to diversify the locations of their storage facilities into different regions so that, if a disruption occurs in one region, companies would be able to satisfy customers' demand from a different region.
- For medium-term disruptions, our study shows that, for different commodities, either underestimation or overestimation leads to the lowest total disruption cost. Therefore, governmental agencies should analyze their navigable inland waterway transportation system to determine which commodities are most predominant. Based on these analyses, agencies would then be able to adjust their estimation strategies to minimize potential economic losses. For example, if a navigable waterway system is highly utilized to transport *coal and coke* and *wheat*, total disruption cost will be lower in the case of duration overestimation.

- In a long-term disruption scenario, it is better overestimate rather than underestimate the disruption duration to minimize total cost. However, repeated overestimation of disruption durations may prompt companies to realize the pattern of overestimation and adjust their behavior accordingly which may be counterproductive to the original objective of minimizing total disruption cost.

3.5 Conclusions

Conducting an economic impact study can be costly in terms of money and time if the study depends on primary data gathered from surveys and interviews. Although a primary data collection approach may lead to more accurate results, the accuracy of a survey-based approach depends on the response rate and response quality of the participants. In this study, a simulation-based economic impact disruption decision model based on publicly available data is introduced. The economic impact of potential disruptive events on the MKARNS is investigated by implementing our model as an illustrative case study. In the case study, a scenario analysis is conducted where the MKARNS is closed down due to a disruptive event for short-term, medium-term, and long-term disruption scenarios. Scenario analysis and our model are utilized to predict the economic losses due to a potential disruption. The model proposed in this study could be applied to different study regions to measure the economic importance of other navigable water systems which can enhance efficiency of federal and state capital allocations.

The findings of the case study show that the expected duration of a disruption determines whether decision makers are better off waiting for the waterway system to reopen or switching to an alternative mode of transportation. Furthermore, estimation accuracy of disruption duration can help the involved stakeholders to reduce total cost caused by the disruptive event. In addition, the relationship between estimated disruption duration and economic loss is found to be non-linear.

In this research, we contributed to the published research pertaining to measuring the economic impacts of disruption response in the navigable inland waterways system. By changing the model parameters, our methodology can be adapted to different study regions, disruption durations, and disruption scenarios. These model parameters can be gathered from publicly available sources, but also researchers can integrate primary data sources into our model. To our knowledge, this research is the only work that comprehensively investigates the importance of disruption duration estimation on the total disruption costs, transportation, penalty, and holding costs related to navigable waterways. Moreover, our system-wide holistic approach will help to better inform the true value of a navigable inland waterway transportation system instead of valuing discrete waterway infrastructure, which can assist transportation authorities to allocate available capital among investment alternatives.

Our methodology is open to new improvements in the future, for example capacity constraints could be introduced to the alternative modes of transportation and port handling resources. Vulnerability of system components could also be considered because a disruption may not impact each system component equally. Some components may be dysfunctional, whereas others may be partially or fully functional. Another extension to consider would be system resiliency. An inland waterway system may not become fully functional at once and instead may gradually gain functionality over a period of time. Another future research direction is to convert total disruption costs to commodity price changes per ton which can be used as an input to multiregional variable input-output (MRVIO) models (Liew and Liew, 1985) to estimate total direct, indirect, and induced impacts in terms of different economic indicators such as output, value-added, employment, employee earnings, and tax collections. Lastly, decision processes corresponding to waiting for the water transportation system to reopen or moving to an alternative mode of transportation is deterministic in our model. However, a more realistic approach may be to incorporate with stochastic parameters such as queue length, decision makers' opinions and experiences, and disruption duration estimation updates during the disruption time frame.

Acknowledgment

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Disclaimer

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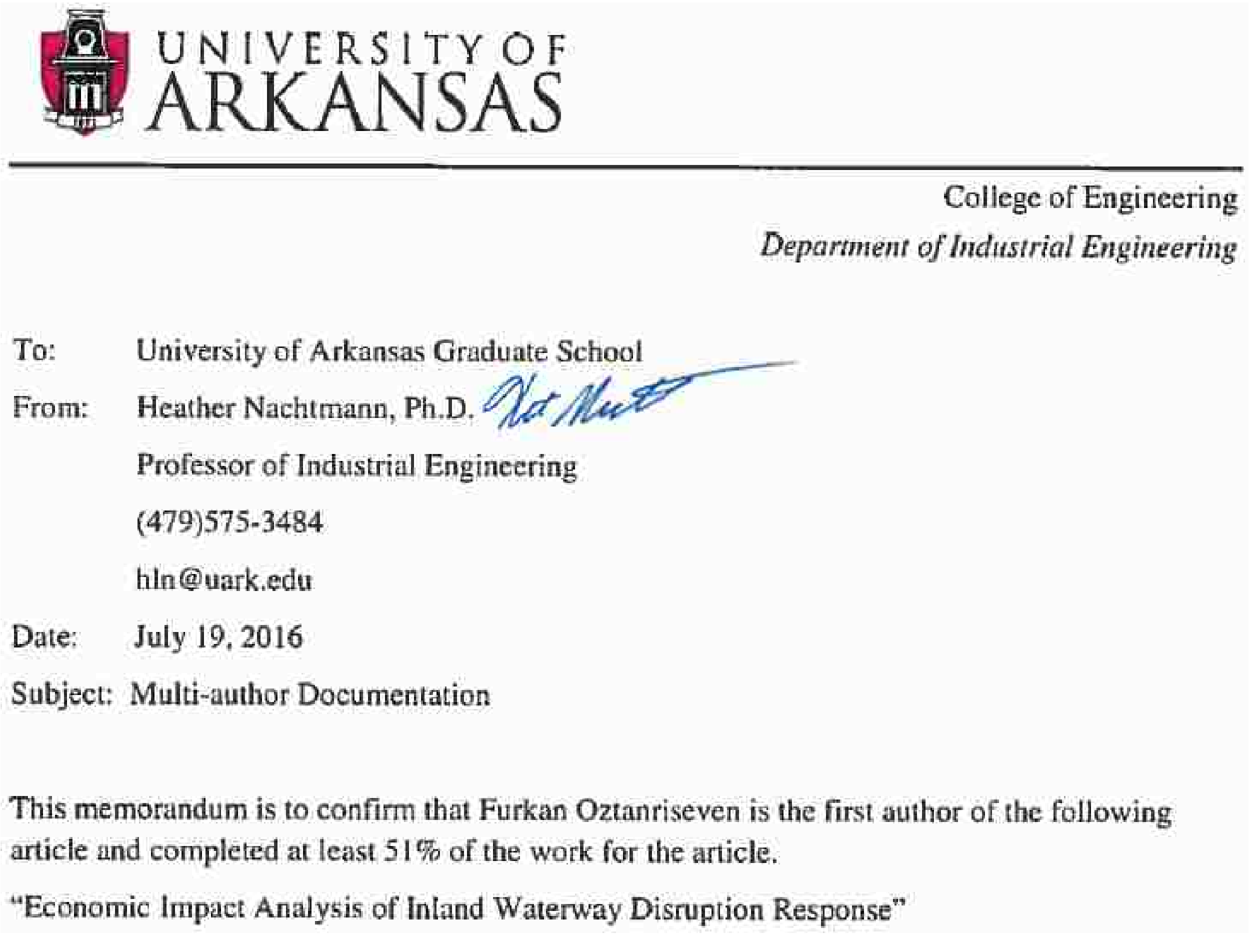
Appendix 1



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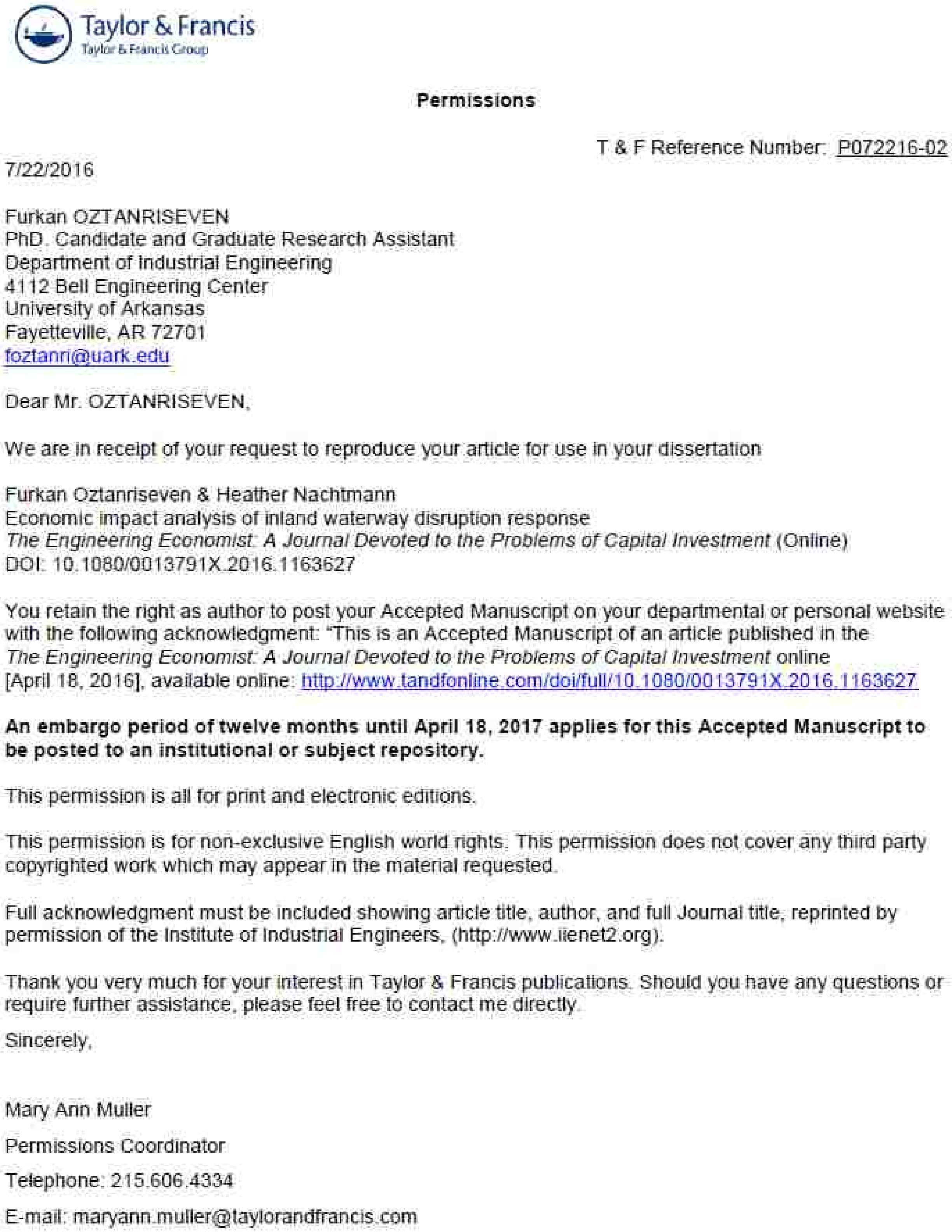
"Economic Impact Analysis of Inland Waterway Disruption Response"

Appendix 2



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4. MODELING DYNAMIC BEHAVIOR OF NAVIGABLE INLAND WATERWAYS

Abstract

Navigable inland waterways link ports located in the heartland of the United States with the rest of the world by providing a fuel efficient and an environmentally friendly mode of transportation. In this research, a maritime transportation simulator (MarTranS) that integrates agent-based modeling, discrete-event simulation, and system dynamics along with a multiregional input-output model is developed to better understand the relationships between inland waterway transportation system components and economic impact factors. To demonstrate these relationships through our model, the McClellan-Kerr Arkansas River Navigation System is used as the case study region. MarTranS is generalizable to any inland waterway transportation system to enable maritime transportation stakeholders to better allocate investment budgets and increase economic benefits.

Keywords: Maritime transportation, inland waterways, agent-based modeling, discrete-event simulation, system dynamics, multiregional input-output model, economic impact

4.1 Introduction

More than ninety percent of global freight is handled by the world's maritime transportation system (IMO, 2013). In the United States (U.S.), approximately one-twelfth of national commodity flow is transported via the inland waterway transportation system (Stern, 2013). Moreover, the inland waterway transportation system, an integrated part of society, economy, and the environment, provides a variety of ancillary benefits including flood protection, power generation, recreation, water supply, and habitats for fish and wildlife (Shepherd, 2014). However, inland waterway transportation is vulnerable to natural disruptions, system component failures, and man-made attacks. Consequently, it is important to understand inland waterway transportation system behaviors to reduce associated risks and mitigate economic losses. It is challenging to study the behavior and economic impacts of the inland waterway transportation system due to high degrees of complexity and uncertainty. As explained by Sterman (2000), inland waterway transportation system complexity exists because: 1) the system is dynamic (Dundovic et al., 2009), 2) its components are tightly coupled (Li & Wang, 2013), 3) system decisions and outcomes are caused by feedback relationships between system components, locks/dams, ports, navigation channels, economy, and the environment (Schade & Schade, 2005), and 4) the effects are not proportional to the causes (nonlinear) due to capacity and budget constraints, system delays, and the subjective nature of decision making processes (Li & Wang, 2013; Köseler, 2008). Therefore, comprehensive modeling techniques are required to accurately represent the complex relationships among system components and how these relationships influence economic impacts. We developed a Maritime Transportation Simulator (MarTranS) that integrates agent-based modeling, discrete-event simulation, and system dynamics along with a multiregional input-output model to model the relationships between the inland waterway transportation system components and economic impact factors.

4.2 Literature Review

Researchers implement a variety of approaches to model complex, dynamic systems, such as time-series models including neural network models (Lyrides et al., 2004) and statistical models (Kavussanos, 2002; Dikos et al., 2006) and static and linear modeling techniques such as cost benefit analysis (Schade & Rothengatter, 2014). However, these approaches have weaknesses that can be overcome by implementing a multimethod simulation approach. In particular, time-series models do not have the capability to consider the causal relationships between the system components (Schade & Rothengatter, 2014) and do not support scenario analysis or reflect the impact of exogenous variables (Schade & Rothengatter, 2014). Static and linear models cannot measure long-term impacts of dynamic complex systems because they do not consider secondary impacts of endogenous variables, and these approaches are heavily data-dependent. Therefore, their output becomes less meaningful for longer study time frames (Schade & Rothengatter, 2014).

Relevant literature related to the use of systems dynamics in maritime transportation is classified and discussed in more detail by Oztanriseven et al. (2014). They classify the reviewed papers as port-related, vessel-related, or other studies. The port-related studies are further grouped into operational or economics focus. The operational studies investigate loading and unloading operations from ship to shore (Dundovic et al., 2009; Dvornik et al., 2006) and berth and yard operations (Cheng, et al., 2010). The remaining port-related studies explore port economics (Ho, et al. 2008; Mingming, 2011; Li & Wang, 2013; Islam & Olsen, 2013). The vessel-related studies investigate shipping freight rates (Randers & Göluke, 2007; Engelen et al., 2009; Dikos et al., 2006) and national fleet development strategies (Wijnolst, 1975). Other studies developed a holistic approach integrating transportation, economy, policies and environment (Schade & Schade, 2005; Fiorello et al., 2010), and qualitative system dynamics approach to investigate the impacts of policy selection decisions (Videira et al., 2012).

Another area of relevant literature is the study of disruptive events and resilience in maritime transportation systems (Perez Lespier et al., 2015). The 9/11 attacks, Los Angeles/Long Beach lockout, and Hurricane Katrina resulted in higher cognizance of public, policy makers, and researchers (Santella & Steinberg, 2009). Scholars conducted research in potential risk scenarios (Lattila & Saranen, 2011), system resiliency (Omer et al., 2012; Croope & McNeil, 2011), and security policy impacts (Yeo et al., 2013). In a recent paper, the current body of knowledge was classified into study regions (Asia, North America, Europe, International, and hypothetical), types of ports studied, intermodal transportation considered, types of causal relations considered (disruption-related, capacity-related, and other), variable classifications, and sensitivity and scenario analysis considerations (Oztanriseven et al., 2014). Moreover, Oztanriseven et al. (2014) classified the relevant literature by simulation period employed (hours, days, months, and years), software utilized (Vensim, Powersim, Stella, iThink, and DYNAMO), modeling challenges (data-related and complexity-related), validation/verification techniques (comparing with historical data, sensitivity analysis, and expert reviews), and the system dynamics methodology as model integration (network optimization, input-output, econometrics, and regression).

Oztanriseven et al. (2014) identify two studies that employed multimethod simulation approaches in maritime transportation. Silva et al. (2011) integrate system dynamics and agent-based modeling to specifically examine manufacturing industries and maritime carriers. Studied agents include industry, third-party logistics, maritime carrier, land carrier and customers (Silva et al., 2011). Furthermore, Silva et al. (2011) develop a causal loop diagram which captures the actions and reactions of the agents' behaviors. Darabi, et al. (2012) use an agent-based simulation to model ships, carriers, and ports and integrate system dynamics to model the interrelationships of other transportation modes including airport, railroad, waterways, pipeline, and highway. The main objective of their work is to illustrate the applicability of multimethod simulation modeling in maritime transportation system. However, model parameters, application, and results are not discussed in their paper.

The literature review presented here indicates that multimethod simulation is a well-suited approach to model the complexities in the inland waterway transportation system. The limited work verifies that there is an opportunity to expand the current body of knowledge in this research area (Potter & Lalwani, 2008; Cheng, et al., 2010).

4.3 Methodology

A better understanding of the relationships between inland waterway transportation system components and economic impacts can lead to improved investment decisions. Therefore, in this research, MarTranS is developed and employed to support more informed inland waterway investment decisions in order to increase economic benefits. Our research objective is to comprehensively describe the economic impacts of inland waterway transportation system under normal operations over a fifty year study time frame to account for long-term impacts. The software utilized to conduct the study is AnyLogic 7.3.

4.3.1 Simulation Model Selection

4.3.1.1 System Dynamics

System dynamics is a computer-based simulation technique that consists of two major elements, the system and its dynamics (Yeo et al., 2013). System dynamics focuses on the interactive relationships between system components (Kirkwood, 1998) based on four theories;

mental problem-solving process, information feedback theory, decision theory, and computer simulation (Schade & Schade, 2005). Causal loop and stock and flow diagrams explain the casual relationships and quantify these complex relationships as the basis of the model (Yeo et al., 2013; Cheng et al., 2010).

System dynamics provides the following modeling advantages: 1) direct impact of system changes can be modeled (Dikos et al., 2006); 2) impacts of structural changes, regulations, and disruptions can be modeled (Dikos et al., 2006); 3) sensitivity and scenario analysis can be conducted (Dikos et al., 2006; Yeo et al., 2013); 4) qualitative knowledge can be integrated into the model (Dikos et al., 2006); 5) simulation can function under insufficient data conditions (Dikos et al., 2006); and 6) model can explain system behavior that continuously changes over a long period of time with time lags (Schade & Schade, 2005; Liu et al., 2010).

North (2005) states that system dynamics might not be an appropriate model approach when the problem studied considers fixed processes, system processes are not well understood or are difficult to aggregate at a high level, system learning and adaption, and/or discrete events exist. In addition, system dynamics does not model geographical impacts on discrete decision variables. Integrating system dynamics with discrete-event simulation and agent-based models can overcome these limitations (North, 2007).

4.3.1.2 Discrete-Event Simulation

Discrete-event simulation utilizes entities, resources, and block charts to illustrate the flow of passive objects such as people or tasks (Borshchev & Filippov, 2004). Discrete-event simulation builds upon Monte Carlo simulation and overcomes the limitations of system dynamics and agent-based models by considering dynamic processes and uncertainty (North, 2007). According to North (2007), discrete-event simulation is an appropriate tool to use when complex processes are examined, the modeler is interested in progress over a specific time period, the process itself is static, and investigated variables contain uncertainty and follow an established probability distribution. Discrete-event simulation can provide operational level insights into the modeled system (Darabi et al., 2012). Limitations of discrete-event simulation are that it cannot explain relationships at a high aggregation level or model adaptive behavior of system components.

4.3.1.3 Agent-Based Modeling

As the world becomes more interconnected, more sophisticated modeling tools, such as agent-based modeling, are required to model a system as individuals and their related behaviors, which are represented as agents (Parunak et al., 1998). Agents can be cars, pedestrians, customers, or even companies (Borshchev & Filippov, 2004), and as individuals that interact with each other, researchers can observe their outcome variables at the system, individual and aggregate levels (Parunak et al., 1998). Agent-based models have been applied to a variety of research fields including organizational behavior, supply chain optimization and logistics, financial markets, and transportation (Macal & North, 2013; Baindur & Viegas, 2011; Douma et al., 2012; Flötteröd et al., 2010; Silva et al., 2011; Darabi et al., 2012). Agent-based modeling is useful for modeling complex and dynamic system structures and when the modeler would like to examine system-wide interrelationships but only has knowledge about individual agent behaviors (Borshchev & Filippov, 2004). Agent-based modeling enables “what if” scenario analysis through changing agent behavior (Parunak et al., 1998). Computational requirements are the biggest challenge in agent-based modeling (Castle & Crooks, 2006).

4.3.2 Model Development

The developed MarTranS supports our research objective by modeling relationships between inland waterway transportation system components (ports, locks/dams, navigation channels, commodities, alternative modes of transportation, and supply and demand nodes) and regional economic impact factors. Our research hypothesis is that a lack of future investment in inland waterway transportation system infrastructure will result in a significant decline of economic impacts in the long-term. The key model components in MarTranS are ports, locks/dams, navigation channel, commodities, alternative modes of transportation, and economic impact factors. In order to estimate long-term economic impacts, a fifty year time frame is considered to study these relationships and economic impacts.

4.3.2.1 MarTranS Structure

The MarTranS structure is illustrated in Figure 1. The sub-models integrated in MarTranS are color coded in Figure 1 as system dynamics (orange), agent-based (yellow), and discrete-event (blue). The input parameters are investments ($), demand changes (tonnage), and the inland waterway transportation system disruptions (days). In our model, available budget funds can be invested in port, lock/dam, and/or navigation channel infrastructure. Since investment amounts can be set by decision makers, investments are defined to be endogenous variables. However, demand changes and system disruptions are exogenous variables since there is little or no control over these variables by model users. These endogenous and exogenous variables impact the discrete event simulation model parameters including port processing times, lockage times, lock unscheduled unavailabilities, lock scheduled unavailabilities, and transportation times.

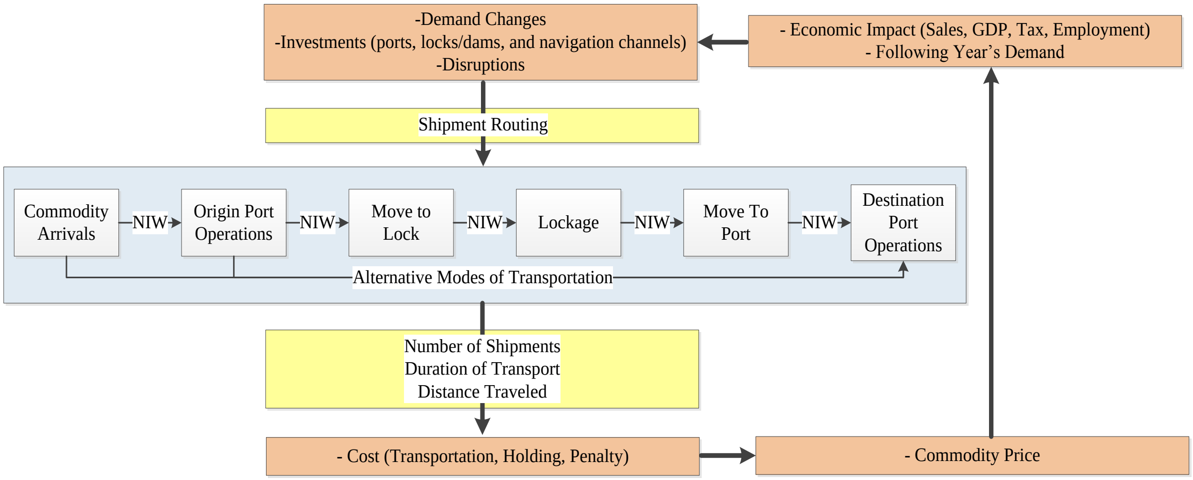

Figure 1 MarTranS Structure

As illustrated in Appendix Figure A3, the discrete-event simulation sub-model starts with commodity arrivals. At this stage, different types of commodities arrive to the ports in the study region. These commodities are grouped into four categories including dry cargo, dry bulk, liquid bulk, and grain. Dry cargo commodities are iron and steel and manufacturing equipment/machinery. Chemical fertilizer, coal and coke, sand/gravel and rock, and minerals and building materials are categorized as dry bulk commodities. Liquid bulk commodities include other chemicals and petroleum products. Finally, grain commodities are wheat, soybeans, and food/farm products. Following commodity cargo arrivals, these commodities spend time in their ports of origin due to port handling activities. Then, the commodities will go through the necessary lock(s)/dam(s), as shown in Appendix Figure A5, which are located between their origin and destination ports. Each lock/dam has its own cargo processing time, number of scheduled unavailabilities, number of unscheduled unavailabilities, time per scheduled unavailability, and time per unscheduled unavailability values (USACE, 2015). We conducted a regression analysis and probability distribution fitting to these lock/dam values in the MarTranS model to account for individual characteristics of each lock/dam. Once these commodities reach their destination ports, they wait in their designated port's offloading queue for the destination port's process to be over, as shown in Appendix Figure A4. After the destination port's operations are completed, these commodities leave the system, with their time spent in the system and distance traveled recorded. These records are collected for one simulation year and are utilized to measure costs: transportation cost, holding cost, and penalty cost in the system dynamics sub-model, as presented in Appendix Figure A6. As illustrated in rectangle 1 in Appendix Figure A6, the number of shipments and average distance traveled values for each type of commodity transported via each mode of transportation are the cost drivers for transportation cost. Similarly, the number of shipments and average time spent in the system are utilized as the cost drivers for holding and penalty costs as shown in rectangles 2 and 3 in Appendix Figure A6. Rectangle 4 in Appendix Figure A6 shows total cost per ton values which is a summation of transportation, holding, and penalty costs. In rectangle 5, the commodity price calculation is illustrated for each commodity type. Commodity price values decrease/increase if the current total cost per ton is less/more than the previous year's total cost per ton. Based on current year's commodity prices, demands for next year and the economic impacts for a given year are calculated in rectangles 6 and 7. These economic impacts are sales, gross domestic product (GDP), tax, and employment. Then, a multiregional input-output sub-model is used to compute the indirect and induced economic impacts.

The agent-based sub-model is utilized to define the behavior and characteristics of agents, which are commodity shipments in our model. Appendix Figure A2 illustrates that each agent has a capacity, origin port, destination port, system entry time, system exit time, type of commodity, current location parameter, and navigation route function. These parameters and function enable the collection of critical information, including number of shipments, agent time spent in the system, and distance traveled in the system, for each commodity in a given year. Therefore, the agent-based sub-model links our discrete-event simulation sub-model with the system dynamics sub-model and routes the sequence of processes for each agent to visit.

4.3.2.2 Model Formulation

In this section, the formulation of MarTranS is explained. The model formulation contains sets, parameters and mathematical equations. The purpose of the model is to comprehensively describe the economic impacts of inland waterway transportation system under normal operations over a fifty year study period. Economic impact is measured with four economic indicators (sales, GDP, tax, and employment) which depend on the quantity of commodity demanded and its respective price in a given year. The quantity demanded and commodity prices depend on the costs associated with moving commodities from their origin to destination nodes. The model formulation is as follows:

Sets	
$i \epsilon I$	Set of commodities
$t \epsilon T$	Set of years
$l \epsilon LD$	Set of lock/dam locations (river mile)
$l' \epsilon S$	Set of port locations (river mile)
$y \epsilon \mathbb{R}_{\geq 0}$	Set of time values
$r \epsilon R$	Set of regions
$q \epsilon Q$	Set of transportation modes q = {1: water, 2: rail, 3: truck, 4: other}
$z \epsilon Z$	Set of economic indicators z = {1: Sales, 2: GDP, 3: Tax, 4: Compensation, 5: Employment}

Parameters	
$\bar{\lambda}_i^q(t)$	Average number of commodity *i* shipments by mode of transportation *q* per day in year *t*
$f_i^q(t)$	Flow of commodity *i* by mode of transportation *q* in tons in year *t*
$\Gamma_i^q(t)$	Capacity of mode of transportation *q* in tons for commodity *i* in year *t*
$B_i(t)$	Capacity of barge carrying commodity *i* by in year *t*
$N_i(t)$	Number of barges per shipment in year *t*
$\Theta\ (t)$	Number of navigable inland waterway (NIW) working days in year *t*
$D_i^q(t)$	Demand for mode of transportation *q* in tons for commodity *i* in year *t*

$\varphi_i^q(t)$	Transportation cost rate of transportation mode *q* per ton mile in year *t*
$\Phi_i^q(t)$	Transportation cost rate of transportation mode *q* per ton in year *t*
$\bar{d}_i^q(t)$	Average travel distance for commodity *i* shipments by mode of transportation *q* in year *t*
$r_i(\mathrm{LD},t)$	Commodity *i* shipments lock/dam processing time in year *t*
$r_i(\mathrm{S},t)$	Commodity *i* shipments port processing time in year *t*
$\Delta t_i^q(r_i(\mathrm{LD},t),\, r_i(\mathrm{S},t))$	Transportation delay in days for commodity *i* shipments by mode of transportation *q* in year *t*
$p_i(t,\Delta t_i^q)$	Commodity *i* shipments by mode of transportation *q* penalty cost rate per day due to Δt_i^q days of delay in year *t*
$P_i(t,\Delta t_i^q)$	Commodity *i* shipments by mode of transportation *q* penalty cost rate per ton due to Δt_i^q days of delay in year *t*
$\bar{\psi}_i^q(t)$	Transportation duration in days of commodity *i* shipments by mode of transportation *q* in year *t*
$\bar{v}_i(t)$	Average price of commodity *i* in year *t*
$h_i(t)$	Commodity *i* holding cost rate per day in year *t*
$H_i(t)$	Commodity *i* holding cost rate per ton in year *t*
$C_i(t)$	Commodity *i* total cost rate per ton in year *t*
$\omega_i(t)$	Commodity *i* inflation rate in year *t*
$\Delta Y_i(t)$	Commodity *i* NIW final demand change in year *t*
$(I-A)^{-1}$	Table of direct and indirect requirements to meet industrial demand levels (*Y*)
$\Delta X_i(t)$	Industry output changes due to the change in commodity *i* in year *t*
$\eta_i(t)$	Commodity *i* demand growth rate in year *t*
$\tau_i(t)$	Commodity *i* price elasticity of demand in year *t*
$\beta_i(t)$	Commodity *i* NIW demand growth rate due to the impact of Panama Canal expansion in year *t*
$w_j(t)$	Flow weight of port that is located at *j* in year *t*
$\overline{\alpha_\iota}(t)$	Average value of commodity *i* per ton in year *t*

Model

$$\bar{\lambda}_i^q(t) = \left(\frac{f_i^q(t)}{\Gamma_i^q(t)\ \Theta(t)}\right) \qquad \forall i\epsilon\mathrm{I};\forall q\epsilon\mathrm{Q};\forall \mathrm{t}\epsilon\mathrm{T} \tag{1}$$

$$\Gamma_i^1(t) = B_i(t)\ N_i(t) \qquad \forall i\epsilon\mathrm{I};\forall \mathrm{t}\epsilon\mathrm{T} \tag{2}$$

$$D_i^q(t) = \Gamma_i^q(t)\,\overline{\lambda}_i^q(t)\ \Theta(t) \qquad \forall i\epsilon\mathrm{I};;q\neq 1;\forall \mathrm{t}\epsilon\mathrm{T} \tag{3}$$

$$\Phi_i(t) = \frac{\sum_{q\epsilon\mathrm{Q}} \varphi_i^q(t)\,\overline{d}_i^q(t)\ D_i^q(t)}{\sum_{q\epsilon\mathrm{Q}}\ D_i^q(t)} \qquad \forall i\epsilon\mathrm{I};\forall \mathrm{t}\epsilon\mathrm{T} \tag{4}$$

$$P_i(t, \Delta t_i^q) = \frac{\sum_{q\epsilon \mathrm{Q}} p_i(t, \Delta t_i^q(r_i(\mathrm{LD}, t), r_i(\mathrm{S}, t)))\, D_i^q(t)\, \bar{v}_i(t)}{\sum_{q\epsilon \mathrm{Q}} D_i^q(t)} \qquad \forall i\epsilon \mathrm{I}; \forall \mathrm{t}\epsilon \mathrm{T} \tag{5}$$

$$H_i(t) = \frac{\sum_{q\epsilon \mathrm{Q}} h_i(t)\, D_i^q(t)\, \bar{v}_i(t)\, \overline{\psi}_i^q(t)}{\sum_{q\epsilon \mathrm{Q}} D_i^q(t)} \qquad \forall i\epsilon \mathrm{I}; \forall \mathrm{t}\epsilon \mathrm{T} \tag{6}$$

$$C_i(t) = \Phi_i(t) + P_i\big(t, \Delta t_i^q(r_i(\mathrm{LD}, t), r_i(\mathrm{S}, t))\big) + H_i(t) \qquad \forall i\epsilon \mathrm{I}; \forall \mathrm{t}\epsilon \mathrm{T} \tag{7}$$

$$v_i(y) = \int_{t-1}^{t} \big(Inflow_i(y) - Outflow_i(y)\big)\, dy + v_i(0) \qquad \forall i\epsilon \mathrm{I}; \forall \mathrm{t}\epsilon \mathrm{T}; \forall \mathrm{y}\epsilon \mathrm{Y} \tag{8}$$

$$Inflow_i(y) = \begin{cases} C_i(t) - C_i(t-1) + \omega_i(t) v_i(t-1) & C_i(t) > C_i(t-1); \forall i\epsilon \mathrm{I}; \forall \mathrm{y}\epsilon \mathrm{Y} \\ \omega_i(t) v_i(t-1) & C_i(t) \leq C_i(t-1); \forall i\epsilon \mathrm{I}; \forall \mathrm{y}\epsilon \mathrm{Y} \end{cases} \tag{9}$$

$$Outflow_i(y) = \begin{cases} C_i(t-1) - C_i(t) & C_i(t) < C_i(t-1); \forall i\epsilon \mathrm{I}; \forall \mathrm{y}\epsilon \mathrm{Y} \\ 0 & C_i(t) \geq C_i(t-1); \forall i\epsilon \mathrm{I}; \forall \mathrm{y}\epsilon \mathrm{Y} \end{cases} \tag{10}$$

$$\Delta Y_i(t) = v_i(t)\, \Delta D_i^1(t) \qquad \forall i\epsilon \mathrm{I}; \forall \mathrm{t}\epsilon \mathrm{T} \tag{11}$$

$$\Delta X_i(t) = (I - A)^{-1}\, \Delta Y_i(t) \qquad \forall i\epsilon \mathrm{I}; \forall \mathrm{t}\epsilon \mathrm{T} \tag{12}$$

$$f_i(t) = \frac{1 + \eta_i(t)}{1 - \omega_i(t)} \sum_{q\epsilon \mathrm{Q}} \left(D_i^q(t-1) + D_i^q(t-1)\, \frac{v_i(t) - v_i(t-1)}{v_i(t-1)} \tau_i(t)\right) \qquad \forall i\epsilon \mathrm{I}; \forall \mathrm{t}\epsilon \mathrm{T} \tag{13}$$

$$f_i^1(t) = \frac{C_i(t-1)}{C_i(t)}\, \frac{f_i^1(t-1)}{\sum_{q\epsilon \mathrm{Q}} f_i^q(t-1)}\, f_i(t)\, \big(1 + \beta_i(t)\big) \qquad \forall i\epsilon \mathrm{I}; \forall \mathrm{t}\epsilon \mathrm{T} \tag{14}$$

$$f_i^q(t) = \left(f_i(t) - \frac{f_i^1(t)}{1 + \beta_i(t)}\right) \frac{f_i^q(t-1)}{\sum_{q=2}^{3} f_i^q(t-1)} \qquad \forall i\epsilon \mathrm{I};\, ; q \neq 1; \forall \mathrm{t}\epsilon \mathrm{T} \tag{15}$$

Equation 1 calculates the average number of shipments for each commodity, transportation mode, and year based on the shipment capacity of mode of transportation q. The shipment capacity calculation of inland waterway system is illustrated in Equation 2 as a function of barge capacity and number of barges per shipment. Next, average number of shipment values calculated in Equation 1 are used in the discrete-event simulation sub-model to generate the shipments' arrivals in the origin nodes based on a Poisson distribution. Equation 3 calculates the demand of each commodity and transportation mode in order to measure transportation cost, holding cost, and penalty cost, as shown in Equations 4-6. The total cost rate per ton is then calculated in Equation 7 by summing the costs calculated in Equations 4-6. Commodity prices are represented as stock variables in the model and their values depend on commodity price inflows and outflows which are calculated in Equation 9 and Equation 10 respectively. The inflow increases with the inflation rate only if the inflation adjusted total cost in the current year is lower than the previous year. However, if the current year inflation adjusted total cost is higher than the previous year, then the inflow has a value equal to the sum of the difference between cost of the current and previous year along with price increase due to inflation. The outflow has a value equal to the cost difference between the current and previous year when the total cost per ton for a given commodity in the current year is lower than that of the previous year. To measure the indirect and induced economic impact for each commodity in a given year, the direct impact (also known as final demand change) is calculated for each commodity as showed in Equation 11. Based on the calculated direct economic impact for each commodity, the economic impacts are calculated by utilizing the IMPLAN multipliers (IMPLAN, 2013). Finally, in Equations 13-15, the commodity flows for each mode of transportation are calculated to generate the shipment arrivals for the following year.

4.3.3 Case Study Analysis

To demonstrate the applicability of MarTranS, a case study of the McClellan-Kerr Arkansas River Navigation System (MKARNS) was conducted. The MKARNS, Figure 2 and Table 1, is a 440-mile navigation system (Tulsa Port of Catoosa, 2016) that enables the States of Arkansas and Oklahoma to trade with forty-two countries (ODOT, 2015). The MKARNS provides ancillary benefits in addition to its economic benefits including providing clean water, habitats for fish and wildlife, recreation, hydropower energy, and reducing flood damage

(ODOT, 2015). Furthermore, if transported MKARNS cargo was transferred to the rail or highway transportation systems, the fuel consumption and CO2 emissions would increase by 40 percent and 270 percent respectively (ODOT, 2015). There are currently eighteen locks/dams, thirteen in Arkansas and five in Oklahoma. Each lock is 110 feet by 600 feet with capacity for eight barges to be served at a time (AOPOA, 2012). The MKARNS system is 45 years old, and the aging infrastructure has become an issue and constraint due to the insufficient funding (AOPOA, 2012). Recently, the MKARNS infrastructure received a condition indicator of D+ and a maintenance indicator of F (AWI, 2015). Understanding the economic impacts of the current MKARNS operations can help maritime stakeholders to make better capital investment decisions related to the system infrastructure.

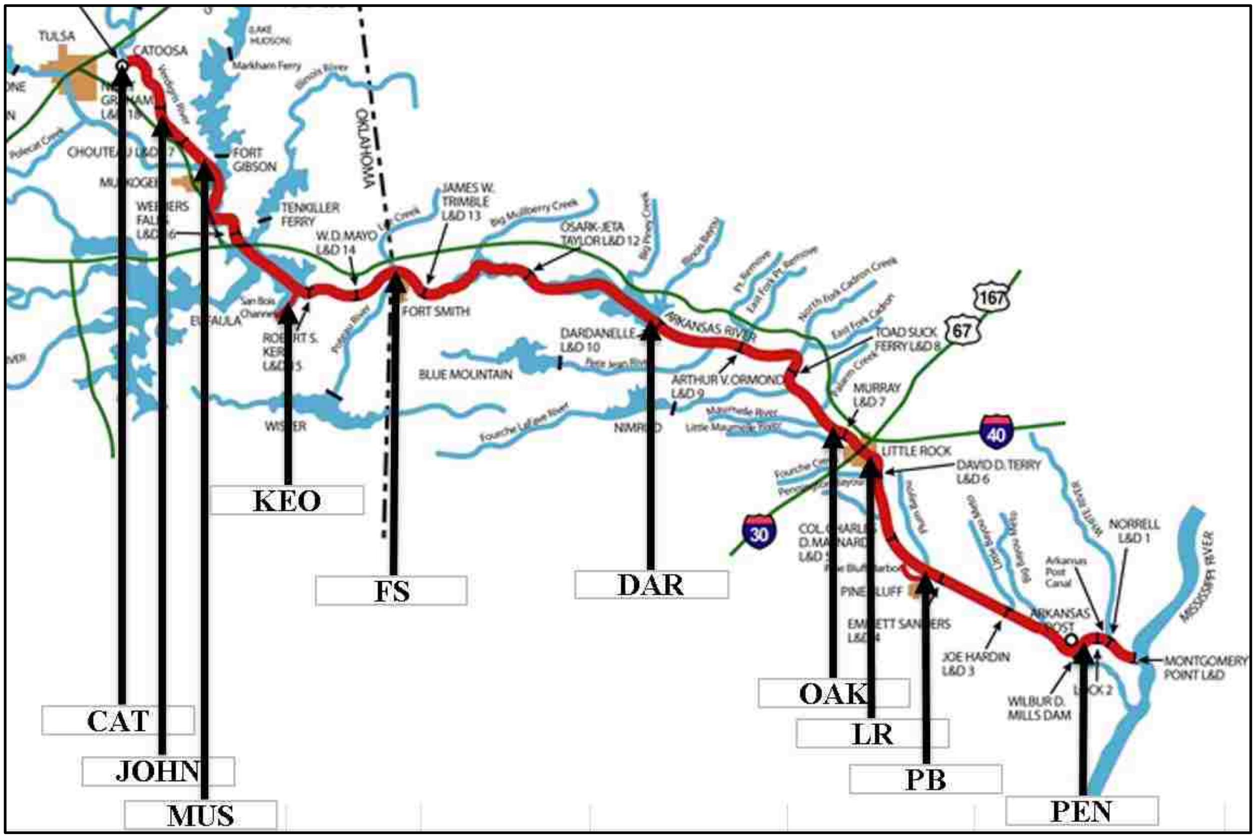

Figure 2 MKARNS Map (USACE, 2015)

Table 1 MKARNS Port Information

Port Name	Code	River Mile
Tulsa Port of Catoosa	CAT	445
Johnston's Port 33 (Oakley)	JOHN	432
Port of Muskogee	MUS	393
Port of Keota	KEO	342
Port of Fort Smith and Five Rivers Dist.	FS	308
Port of Dardanelle (Oakley)	DAR	202
Port of North Little Rock (Oakley)	OAK	116
Port of Little Rock	LR	113
Port of Pine Bluff	PB	72
Port of Pendleton (Oakley) and Riceland	PEN	22

The data sources for each model parameter are presented in Table 2. To facilitate ease of implementation of the model to other inland waterway transportation systems, the primary data collection effort was minimized.

Table 2 Data Sources

Description	Parameter	Source
Commodity flow	$f_i^p(t) \sim Poisson(\bar{\lambda}_i^q(t))$	USACE (2014)
Barge capacity	$B_i(t) \sim Tri(1400,1450,1500)$	IDOT (2008)
# of barges per shipment	$N_i(t) \sim Tri(6,8,17)$	Arkansas Waterways Commission (2011)
Train capacity	$\Gamma_i^2(t)$ = 11,200 tons	ODOT (2015)
Truck capacity	$\Gamma_i^3(t)$ = 26 tons	ODOT (2015)
Lockage time	$r_i(\mathrm{LD}, t)$	USACE (2015)
Port processing time	$r_i(\mathrm{S}, t)$	Port Websites
# of working days in a year	$\Theta(t)$=365 days in a year	AOPOA (2012)
Port weight factor	$w_j(t)$	Higginbotham (2014)
Mode q usage rate	$u_q(t)$	USDOT (2010)
Commodity value	$\bar{v}_i(t)$	AOPOA (2012)
Transportation cost rate	$\varphi_i^q(t)$	Guler, et al. (2012)
Penalty cost rate	$p_i(t, \Delta t_i^q) = .014 * \bar{v}_i(t), \quad \Delta t_i^q > 1\ week$	Painter and Whalen (2010)
Holding cost rate	$h_i(t)$=0.0007 $\bar{v}_i(t)$	Lewis, et al. (2006)
Inflation rate	$\omega_i(t)$	(BLS, 2015)
IMPLAN multipliers	$(I - A)^{-1}$	(IMPLAN, 2013)
Demand growth rate	$\eta_i(t)$	USACE (2014)
Price elasticity of demand	$\tau_i(t)$	(Zhu, 2012)

4.4 Results

In this section, the results of the MKARNS case study is discussed. The results are illustrated in terms of four economic indicators (sales, GDP, tax, and employment) in addition to other performance measures, such as commodity flow and port utilization. As illustrated in Figure 3, the total GDP impact increases from $7 billion in year 2016 to $8.7 billion in year 2022. This gradual increase is caused by the higher demand of the MKARNS due to the inland waterway transportation system efficiency. However, after year 2022, it is observed that the MKARNS GDP impact begins to decline due to increased lock/dam disruptions. This decline in the GDP impact lasts until year 2034 when the MKARNS reaches an equilibrium of approximately $1 billion. The results validate our research hypothesis that a lack of future investment in the inland waterway infrastructure will result in a significant decline of economic impact in the long-term. The largest components of the total GDP impact are generated by the transport of dry cargo and dry bulk commodities.

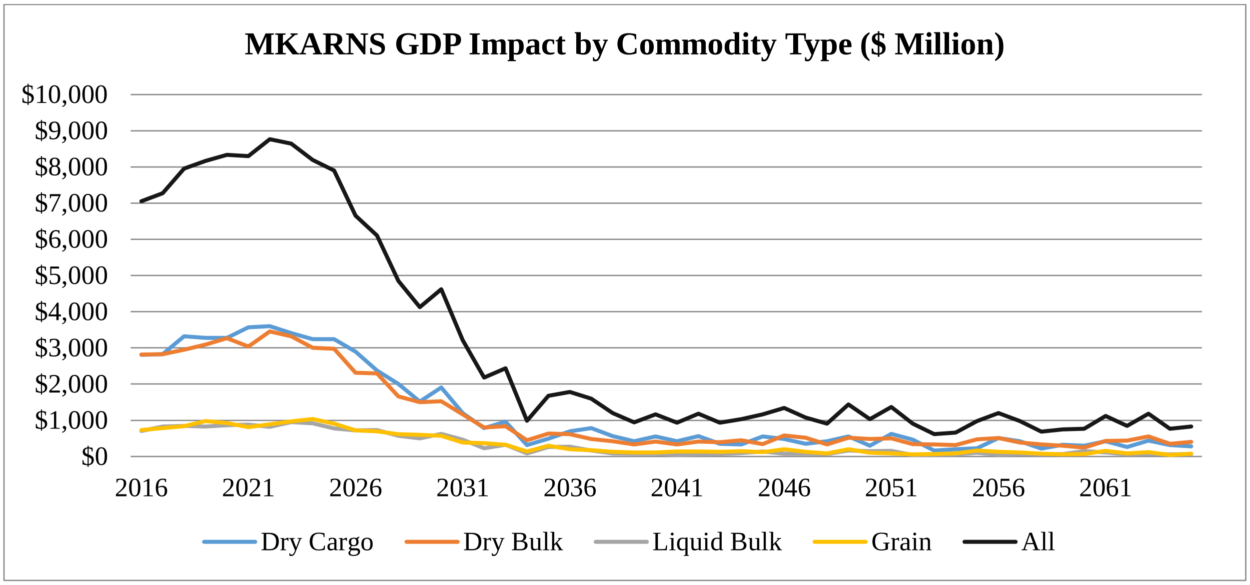

Figure 3 MKARNS GDP Impact by Commodity Type

Figure 4 shows the MKARNS commodity flows over the fifty year time frame. Commodity flows behave similarly to the behavior of the GDP impacts illustrated in Figure 3. The total MKARNS commodity flow in year 2016 is estimated to be 13 million tons, and the total flow increases to 18 million tons by year 2019. This increasing trend in the flow cannot be sustained after year 2019 due to increased lock/dam disruptions. Hence, the total commodity flow then declines rapidly after year 2024 and continues to oscillate around 1.5 million tons (approximately ten percent of the initial flow) for the remainder of the study period. The biggest component of the tonnage flow is dry bulk followed by grain.

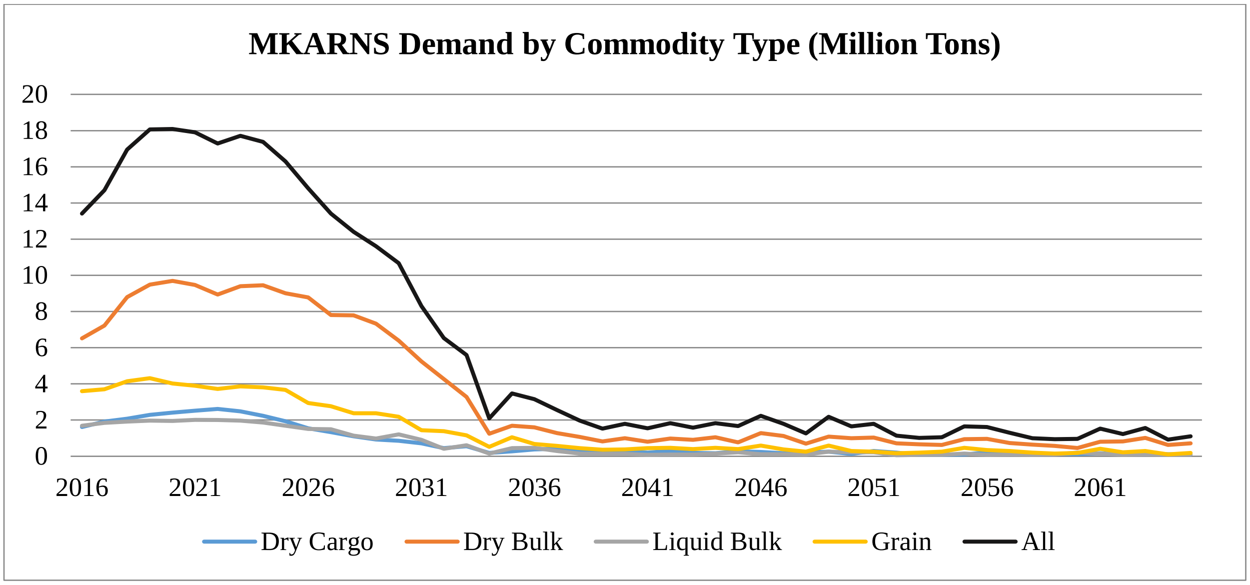

Figure 4 MKARNS Demand by Commodity Type

Another performance measure examined in the model is port utilization which is measured as the average percentage of time that ports are operating in a given year. The port utilization values for all commodities are illustrated in Figure 5. Based on our model results, liquid bulk ports have the highest utilization rates. Analyzing Figure 5, it is observed that most ports follow a similar pattern irrespective to the commodity type; that is, an increase in utilization initially while the commodity flows increase followed by a decrease in the utilization due to the decrease in the MKARNS commodity flows. As illustrated in Figure 5, some port experience a higher rate of utilization. For instance, five dry cargo ports, six liquid bulk ports, and six grain ports exceeded the port utilization rate of eighty percent. These dry cargo ports are: 1) Tulsa Port of Catoosa, 2) Johnston's Port 33 (Oakley), 3) Port of Muskogee, 4) Port of Fort Smith and Five Rivers Distribution, and 5) Port of Pine Bluff. The liquid ports are: 1) Tulsa Port of Catoosa, 2) Johnston's Port 33, 3) Port of Muskogee, 4) Port of Dardanelle (Oakley), 5) Port of Little Rock, and 6) Port of Pine Bluff. The grain ports are: 1) Tulsa Port of Catoosa, 2) Johnston's Port 33, 3) Port of Muskogee, 4) Port of Keota, 5) Port of Dardanelle (Oakley), 6) Port of Pine Bluff. However, the dry bulk ports do not even reach seventy percent utilization rate due to their excess capacities.

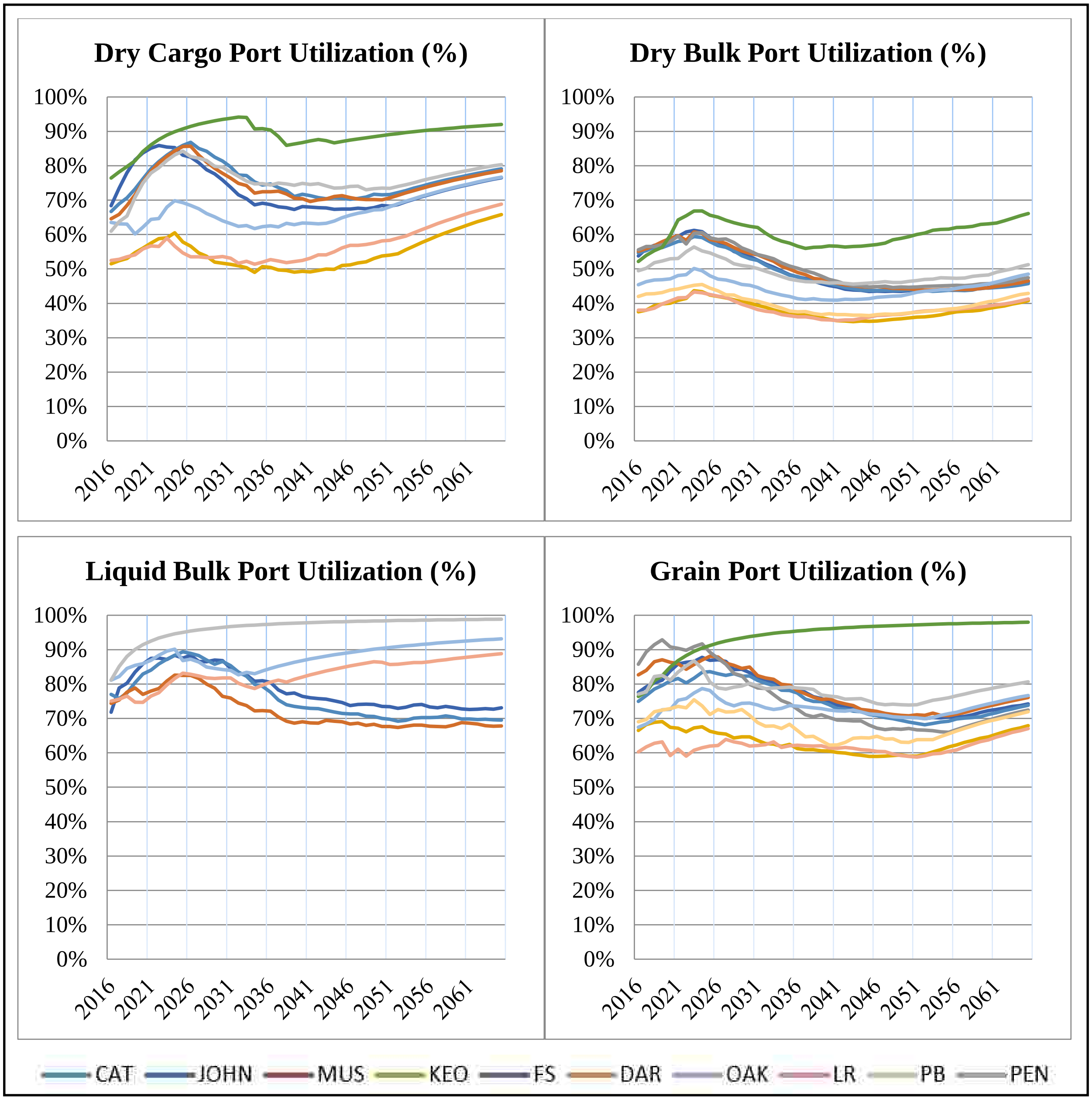

Figure 5 MKARNS Port Utilizations by Commodity Type

Figure 6 demonstrates utilization for all eighteen locks/dams located in the MKARNS. In the year 2016, all locks have a utilization rate of less than sixty percent. Due to the scheduled unavailability and unscheduled unavailability disruptions utilization rates increase over the fifty year study time frame. It can be observed that *Lock 5*, *Lock 2*, and *Lock 10* reach utilization rates above ninety percent, and *Lock 13* and *Lock 15* reach utilization rates above eighty percent.

These high utilization rates indicated higher priority for rehabilitation investments to decrease associated lock delays.

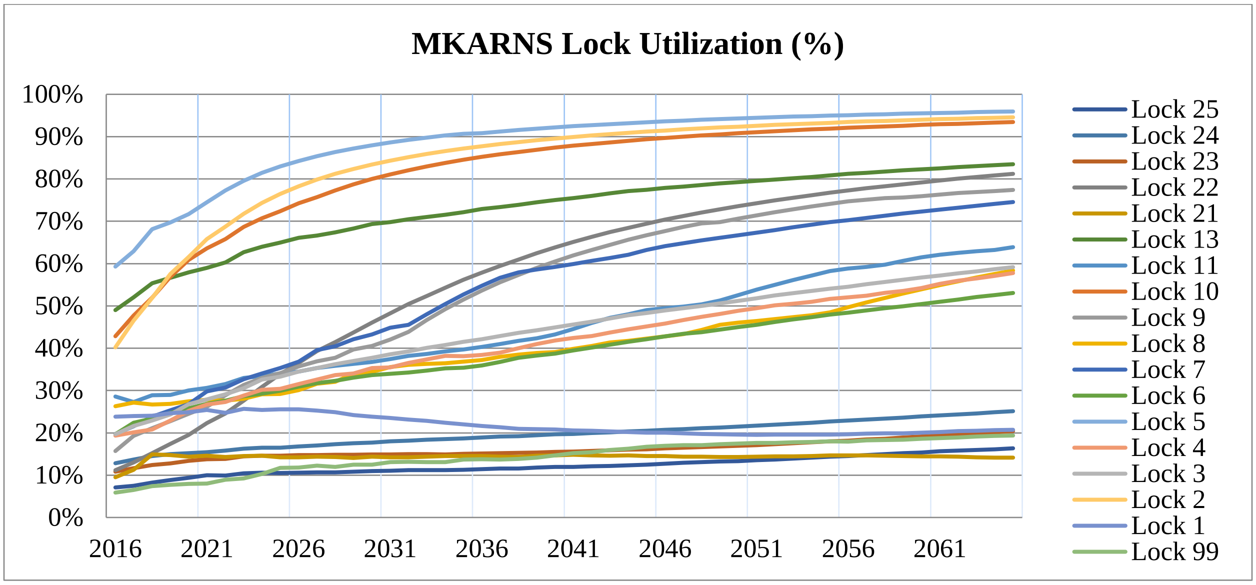

Figure 6 Lock Utilization Performance

The overall performance measurement of sales, GDP, tax, and employment economic indicators are presented in Table 3. Net present value (NPV), based on an assumed 2.4 percent flat inflation rate (BLS, 2015), sales, GDP, and tax economic impacts are $232.5 billion, $111.3 billion, and $7.8 billion for the fifty year study period respectively. On average, sales, GDP, and tax economic impacts are $4.7 billion, $2.2 billion, and $156 million annually respectively. An average of 36,012 jobs are generated every year directly or indirectly due to the MKARNS navigation activities. The coefficients of variation values near one hundred percent indicate the importance of predictive modeling techniques like MarTranS. The main reason for the high variation is the increasing number of disruptive events on the locks/dams. The flow values, tonnage traveled via the MKARNS, are also summarized in Table 3 with an average annual flow of 4.7 million tons which is approximately one third of the flow in the year 2016. Dry cargo and dry bulk account for seventy-seven percent of total flow. Average port utilization is highest for the liquid bulk and lowest for the dry bulk with eighty-one percent and forty-five percent respectively. Lastly, it can be observed that the total cost of transportation per ton ranges between $55.05 and $59.01, and this cost results in a five to twenty-seven percent of commodity price per ton in the MKARNS study region.

Table 3 MKARNS Performance Measures

		NPV Sales ($M)	NPV GDP ($M)	NPV Tax ($M)	Emp. (#Jobs)	Flow (ton/year)	Port Util.
Dry Cargo	**Mean**	$86,846	$44,722	$2,922	14,412	559,352	68%
	CV	100%	100%	100%	100%	117%	5%
Dry Bulk	**Mean**	$89,963	$41,999	$3,505	13,666	2,587,032	45%
	CV	96%	96%	96%	96%	113%	8%
Liquid Bulk	**Mean**	$26,820	$11,854	$600	3,794	497,872	81%
	CV	102%	102%	102%	102%	114%	3%
Grain	**Mean**	$28,895	$12,738	$776	4,140	1,046,320	72%
	CV	95%	95%	95%	95%	107%	4%
All	**Mean**	$232,525	$111,313	$7,803	36,012	4,690,576	53%
	CV	97%	97%	97%	97%	112%	6%

4.5 Conclusions and Future Work

This paper presents the development and implementation of a maritime transportation simulator (MarTranS) to study the interactions between inland waterway transportation system components and economic impact factors. Successful implementation of our model can help stakeholders make informed inland waterway infrastructure investment decisions to improve economic performance. By utilizing publicly available data, MarTranS parameters can be changed, and the model can be applied to any inland waterway transportation system. To the best of our knowledge, this is the sole study that measures the economic impacts of navigable inland waterways transportation system dynamically throughout the time-span with the use of multimethod simulation model.

To demonstrate the value of MarTranS, we conducted a case study of the MKARNS. Our case study illustrates that the economic performance of the MKARNS is not sustainable in the long-term without future investment in MKARNS infrastructure. Model results show that in approximately two decades, the economic impacts and commodity flow will drop to only ten percent of their current values. Moreover, seventeen ports and five locks/dams reach utilization rates over eighty percent. These high utilization rates create increased transportation delays and costs.

System dynamics based models are criticized for their lack of available formal validation techniques (Barlas, 1994). To ensure that MarTranS generates accurate and reliable results, five validation tests discussed in the relevant literature are conducted in this study. The five validation tests utilized are boundary adequacy, structure assessment, dimensional consistency, parameter assessment, and extreme condition (Sterman, 2000). First, in the boundary adequacy test, the defined model boundaries in the MKARNS case study are based on the literature review and viewpoints of the Arkansas Waterways Commission and Oklahoma Department of Transportation subject matter experts. Model boundaries must match the purpose for which the model is designed to ensure MarTranS can be used with confidence and must include all of the important factors affecting the behaviors of interest. Moreover, several causal loop and stock and flow diagrams were developed and discussed with the two public waterway transportation agency subject matter experts to confirm that important system feedback relationships were not omitted and exogenous and excluded variables were well defined in the MarTranS. Secondly, the structure assessment test helped us to understand if basic real-world behaviors are violated. For instance, commodity price and quantity demanded results cannot be negative during a MarTranS simulation experiment. This ensures that the structure of the MarTranS matches the structure of the real world inland waterway transportation system being modeled. Third, a dimensional consistency test was conducted to ensure unit consistency between the MarTranS components. Fourth, a parameter assessment test was conducted empirically by comparing the model equations with generalized knowledge and theoretically by comparing model equations with the current literature (Barlas, 1994). For example regression analysis and distribution fitting are conducted to estimate processing time, number of scheduled unavailabilities, number of unscheduled unavailabilities, time per scheduled unavailability, time per unscheduled unavailability values for each lock/dam to account for historical data trends and the cost parameters are defined based on current literature. Lastly, extreme condition tests were conducted by eliminating the scheduled and unscheduled lock/dam unavailabilities from the model and conducting a direct review of each model equation to examine the robustness of the MarTranS.

Ongoing research is expanding this work. Scenario analysis being conducted to study the effect of the Panama Canal Expansion on the inland waterway transportation. Different types of disruptions are being examined to estimate their potential economic impacts. The economic impacts of investing in ports, locks/dams, and navigation channel are also being studied. Long-term extensions of this research include: 1) an optimization model can be integrated into MarTranS to find the best simulation parameters, 2) the tax generated in the model can be considered for reinvestment into the system, 3) MarTranS can be applied to model the entire inland waterway transportation system in the United States, 4) alternative modes of transportation can be modeled in more detail to expand the capabilities of MarTranS, and 5) more detailed analysis could be conducted to further explore the relationship between capital investments and inland waterway transportation system infrastructure reliability. Future extensions will further assist decision making in inland waterway transportation system and can result in a competitive advantage for the U.S. and regional economies.

Acknowledgment

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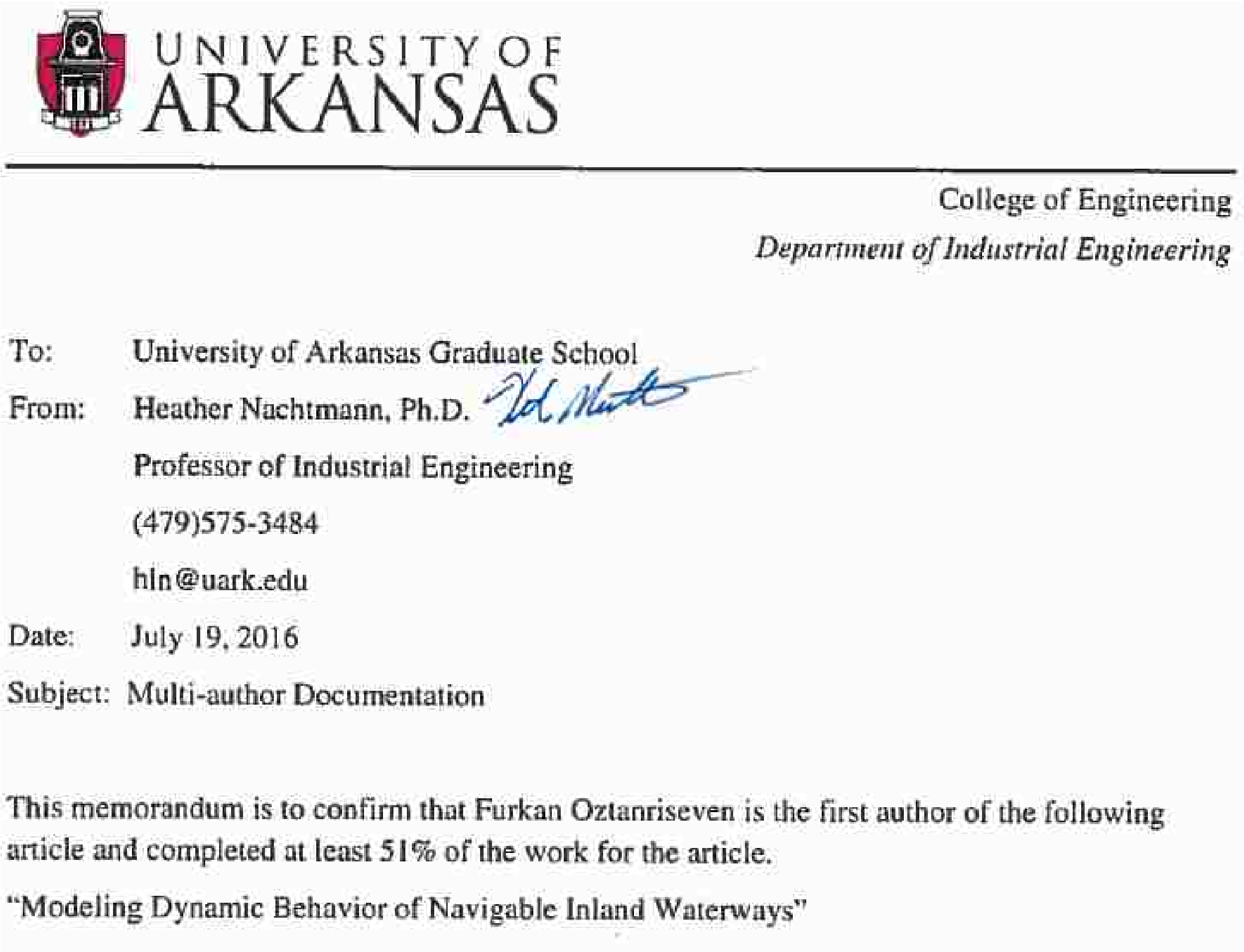
Disclaimer

Appendix 1



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Subject: Multi-author Documentation

This memorandum is to confirm that Furkan Oztanriseven is the first author of the following article and completed at least 51% of the work for the article.

"Modeling Dynamic Behavior of Navigable Inland Waterways"

Appendix 2

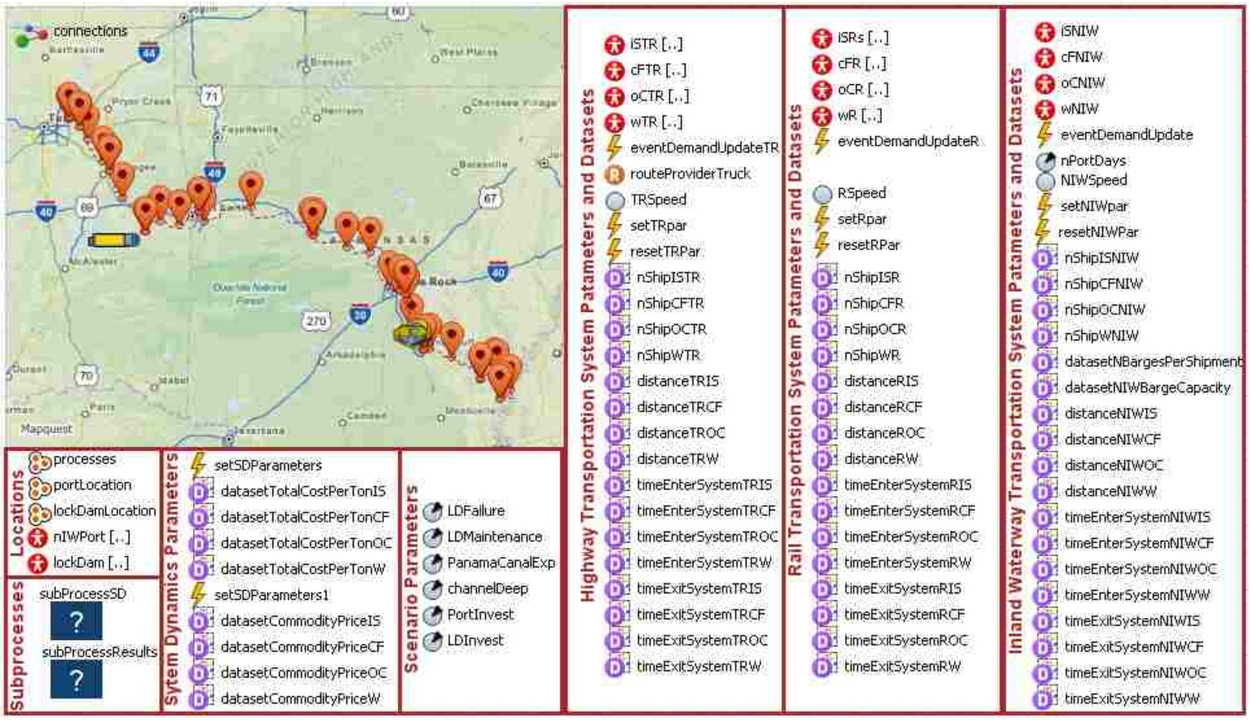

Figure A1 Geographic Information Systems Map and Model Parameters

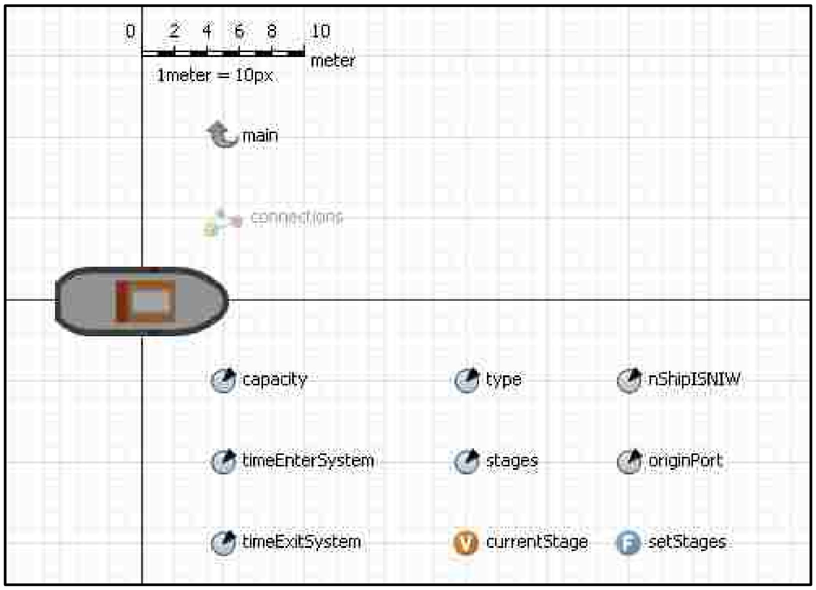

Figure A2 A Sample Agent Parameters

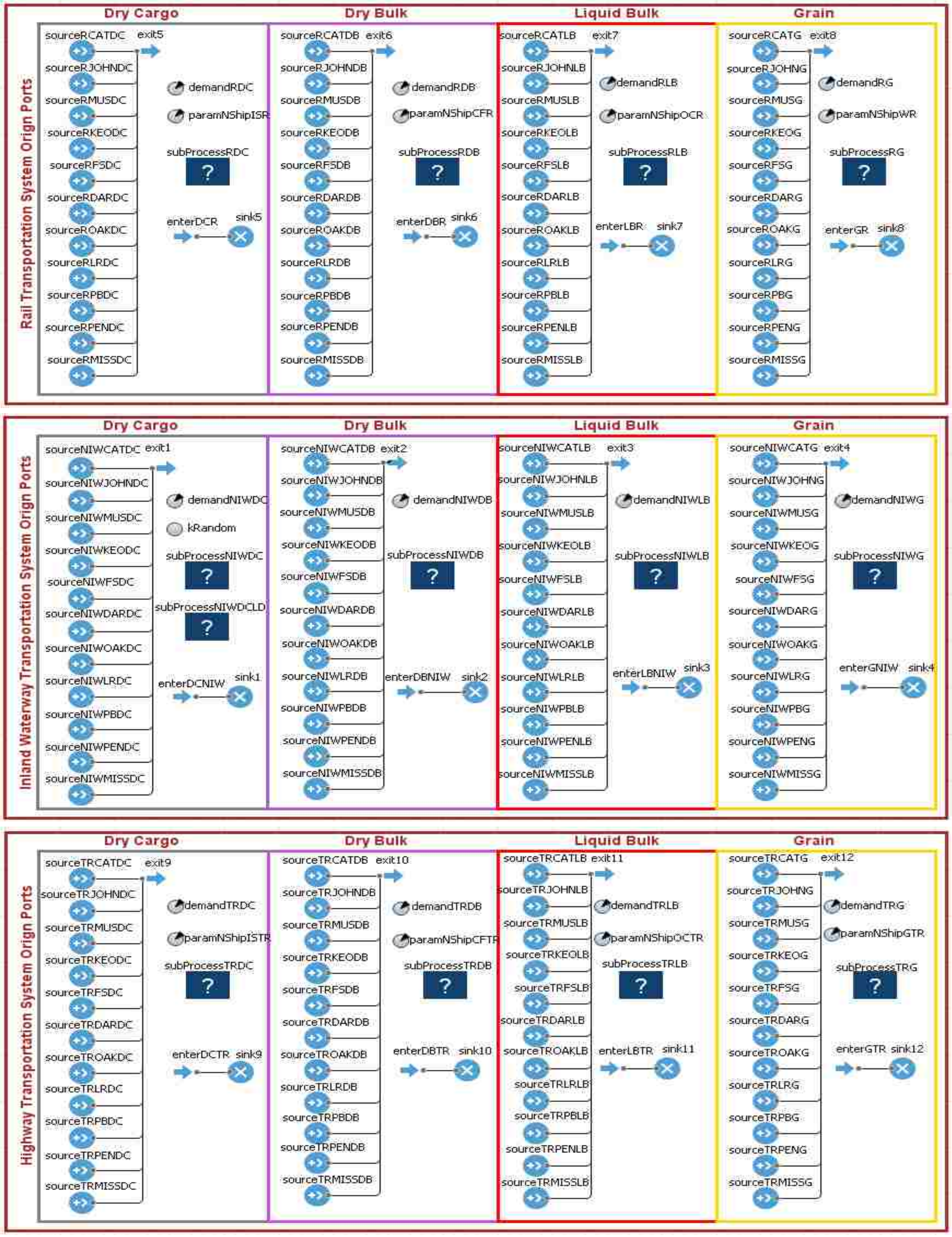

Figure A3 Origin Ports and Discrete-Event Simulation Sub-processes

Figure A4 Dry Cargo Destination Port Processes

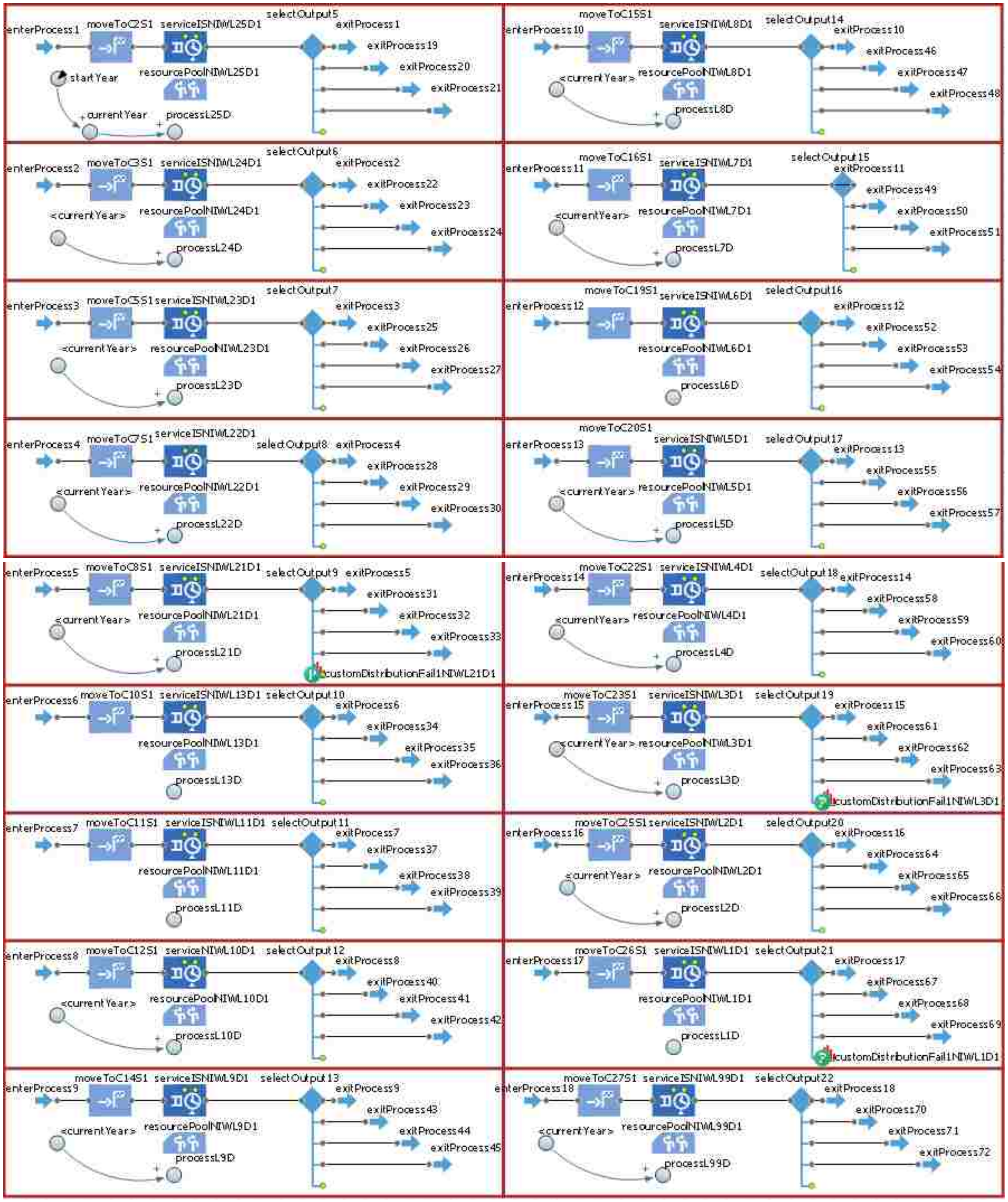

Figure A5 Lock/Dam Processes

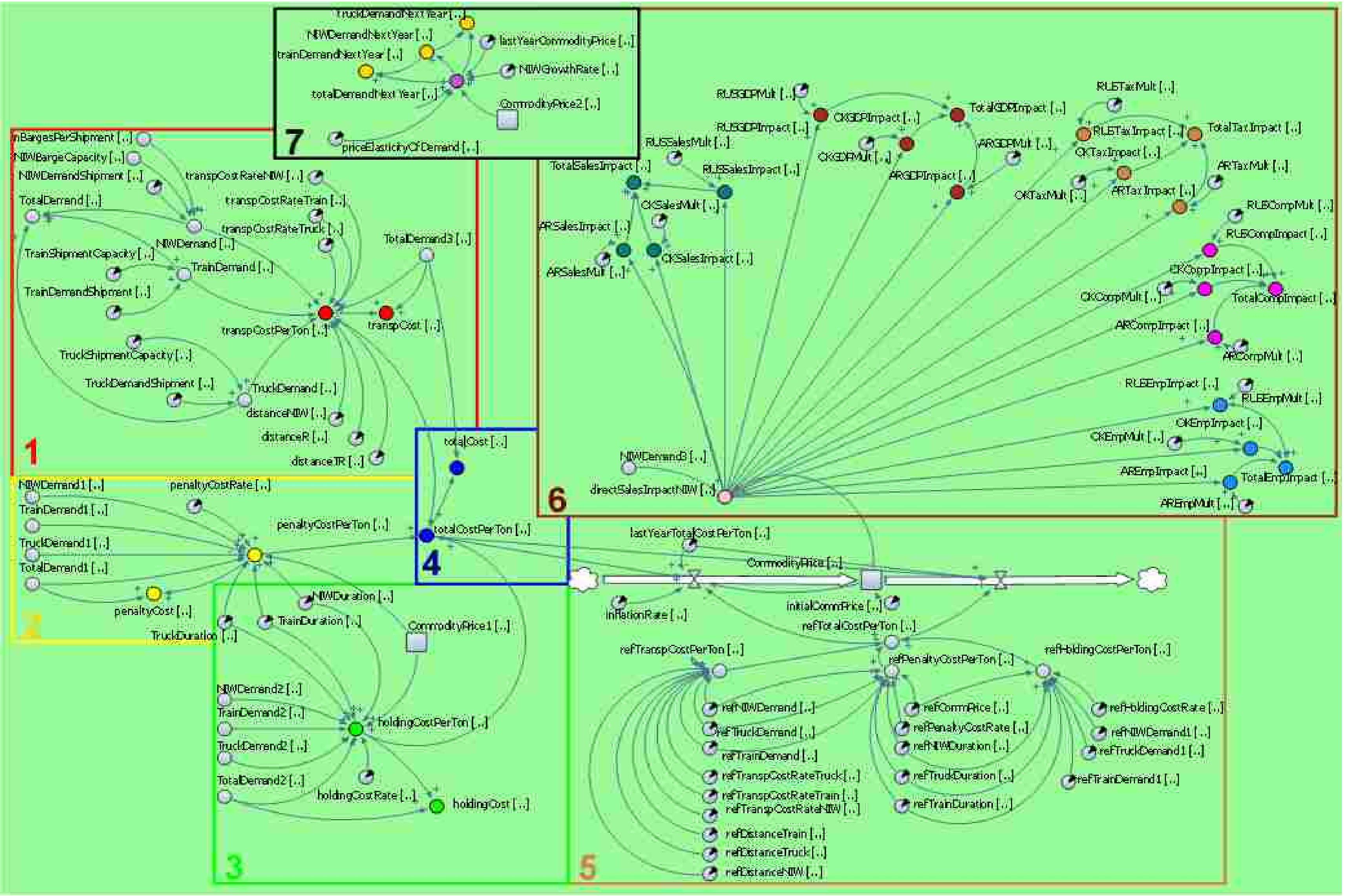

Figure A6 System Dynamics Model of the Inland Waterway Transportation System

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5. STUDYING THE ECONOMIC BEHAVIOR OF THE INLAND WATERWAY TRANSPORTATION SYSTEM

Abstract

The United States inland waterway transportation system (IWTS) connect the Nation's heartland with the global supply chain. The IWTS is challenged with aging infrastructure and limited operations and maintenance budgets which can cause transportation delays and economic losses. The IWTS experienced losses of $33 billion in 2010 due to transportation delays, and American Society of Civil Engineers (ASCE) estimated that these losses will increase to $49 billion by 2020. In this study, real world scenario analyses are conducted to examine the economic impacts of inland waterway transportation system. These scenarios include a base scenario where the system infrastructure remains unchanged and no future investments are made, four investment scenarios (deepening of navigation channel, port expansion, lock/dam rehabilitation, and system-wide investment), two disruption scenarios (lock/dam scheduled and unscheduled unavailabilities), and a demand change scenario focused on impacts of the Panama Canal expansion. The scenario analyses are performed for the McClellan-Kerr Arkansas River Navigation System (MKARNS) utilizing the Maritime Transportation Simulator (MarTranS). The results of our study show that MKARNS locks/dams are the primary source of system delays to future performance.

Keywords: Maritime transportation, navigable inland waterways, agent-based modeling, discrete-event simulation, system dynamics, multiregional input-output model

5.1 Introduction

The United States maritime transportation system is an important component of the global supply chain, and the system generates more than 13 million jobs and $649 billion of gross domestic product (GDP) annually (MARAD, 2013). Navigable inland waterway (NIW) systems are responsible for the efficient flow of goods within the U.S.. The nearly 12,000 miles of the navigable inland waterway (NIW) system in the U.S. handles fifteen percent of the Nation’s transported freight by weight (USACE, 2012). This flow accounts for approximately twenty percent of coal and twenty-two percent of petroleum transportation in the U.S. (USACE, 2009). If the U.S. inland waterway commodity flow was diverted to rail or highway transportation, there would be 6.3 million additional rail cars or 25.2 million additional trucks traveling on the railroads or highways respectively (USACE, 2012). In addition to economic benefits, the inland waterways has ancillary benefits including fish and wildlife habitats, flood protection, clean water supply, hydropower energy, and recreation (IMTS, 2010). Impacting future benefits, the aging inland waterway infrastructure is causing an increase in system delays (USACE, 2012). The majority of these delays are caused by scheduled unavailability and unscheduled unavailability lock/dam disruptions which have continuously increased over the last two decades (USACE, 2012). Therefore, in order to maintain and preferably increase the economic and ancillary benefits, it is necessary to understand the vital elements that comprise the NIW transportation system and how these elements interact to create economic benefits (MARAD, 2013).

In order to improve future inland waterway operations and to better inform future investment decisions, it is necessary to predict and interpret future performance of the NIW transportation system. We utilize the Maritime Transportation Simulator (MarTranS) developed by Oztanriseven and Nachtmann (2016) to study a variety of real world scenarios impacting inland waterway transportation. As shown in Figure 1, these scenarios include a base scenario where the system infrastructure remains unchanged and no future investments are made, four investment scenarios (deepening of navigation channel, port expansion, lock/dam rehabilitation, and system-wide investment), two disruption scenarios (lock/dam scheduled and unscheduled unavailabilities), and a demand change scenario focused on impacts of the Panama Canal expansion.

MarTranS (Oztanriseven & Nachtmann, 2016) integrates agent-based modeling, discrete-event simulation, and system dynamics along with a multiregional input-output model to model and predict future inland waterway transportation system behavior. By predicting the economic impacts of the different real world scenarios, we will evaluate and comprehend how each or a combination of some of the scenarios affect the inland waterway transportation system's behavior from an economic perspective. The results of this analysis improve future infrastructure investment decisions and contribute an increase of jobs generated and an increase in GDP. In consequence, our research hypotheses are: 1) Investments in the current bottlenecks (primary sources of system delays) in the NIW system will increase the system's economic impacts. 2) Investment in non-bottleneck components will not result in the same level of increase as investment in bottleneck infrastructure, 3) Investing in a combination of system components will generate a greater economic impact than investing in each individual component due to the nonlinear relationships between the system components, 4) Increasing number of system disruptions will cause decrease the demand for the NIW system which will result in the greater economic losses, and 5) Increase in demand of the NIW system due to exogenous factors such as the impact of the Panama Canal Expansion will create a limited economic impact improvement due to system congestion. To demonstrate the applicability of MarTranS, the McClellan-Kerr Arkansas River Navigation System (MKARNS) is utilized as the case study region for this research.

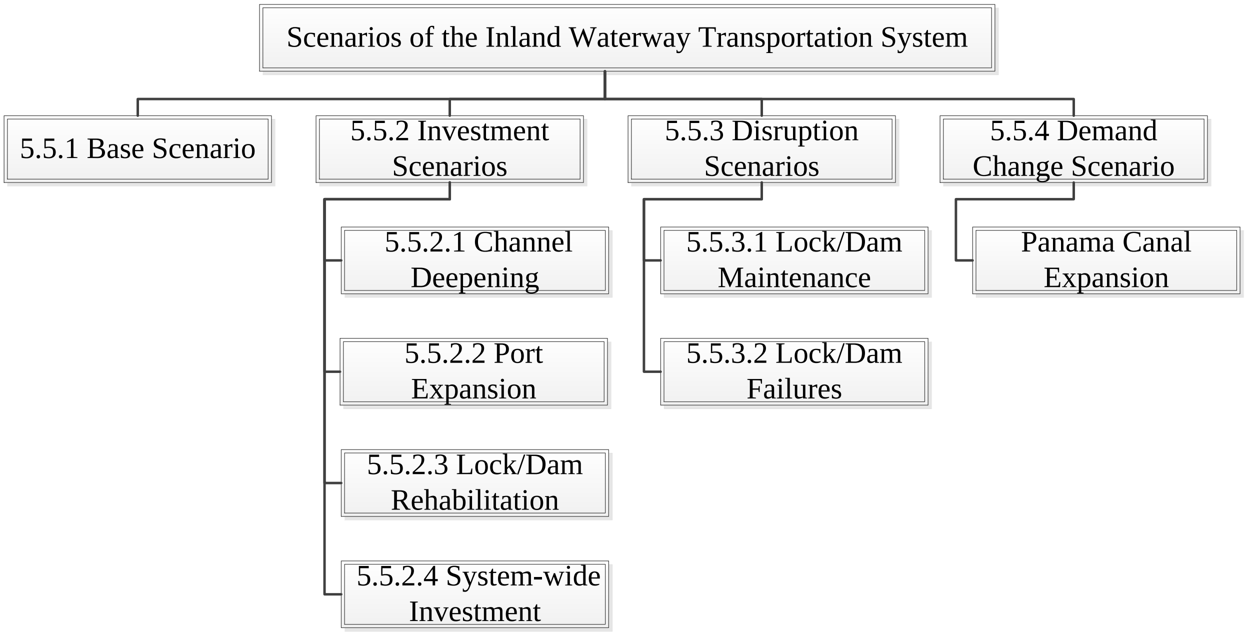

Figure 1 Breakdown of Scenario Analysis

5.2 Literature Review

A comprehensive literature review is conducted in the research areas of maritime transportation system potential disruption impacts, system dynamics in maritime transportation systems, and studies on coastal container ports. Furthermore, a review of navigable inland waterway transportation literature including studies related to lock/dam and channel deepening is conducted. This broad literature review identified the limited amount of work that dedicated to the modeling and measurement of the economic impacts that navigable inland waterway systems can have under real world analyses.

The motivation of this research emerged from interdependent relationships between economic impacts and transportation infrastructure. Santos (2006) stated that many industries depend on transportation, and therefore the economic impacts of transportation infrastructure can exceed beyond the transportation industry itself. Transportation is essential for the effective flow of goods and for many industries to continue with their normal day to day operations. Therefore, navigable inland waterway transportation systems can be beneficial to other modes of transportation along with other influential economic impacts. Moreover, highway and railway congestion in the United States are reaching critical levels. Hence, to reduce the congestion and negative economic impacts, studying the operations and economic importance of NIW is crucial at a regional and national level (Pant et al. , 2015).

To study the economic impacts of navigable inland waterway transportation systems, simulation models are suggested and used by scholars to handle the complexity of the system (Oztanriseven & Nachtmann, 2016; Oztanriseven et al., 2014; Luo & Grigalunas, 2003; Thiers & Janssens, 1998; Almaz & Altiok, 2012). Inland waterway transportation systems include a high degree of interdependencies in ports and locks/dams which make them a suitable candidate for the application of simulation models (Carroll & Bronzini, 1973).

One area of the related literature studies disruption impacts of maritime transportation system. For example, Pant et al. (2015) studied disruption impacts on inland waterway components, such as ports and channels. Similarly, Pant et al., (2011) simulated inland waterway port operations including commodity arrival, unloading, sorting, and distributing. The former studied dock closures, and the latter studied two week closure due to terminal closure, crane outage, departure stoppage. These studies used a multiregional input-output model to measure the total economic impact. Pant et al. (2011) stated that very limited attention is given to the application of dynamic multiregional interdependency models in inland waterway transportation system. The results of these studies indicated that the economic impact of the closures at the Port of Catoosa, located in Tulsa Oklahoma, would be more than $180 million. Another disruption research is conducted by (Kajitani, et al., 2013), where the economic impact of an explosion case study in the Singapore Strait due to transportation cost increases is studied. A more detailed study conducted by Oztanriseven and Nachtmann (2013) discusses disruption research in the maritime transportation sector.

Another area of the relevant literature focuses on the application of system dynamics methodology in maritime transportation settings, which is presented comprehensively by Oztanriseven et al. (2014). The system dynamics literature is classified by Oztanrieseven et al. (2014) into study region, types of ports studied, intermodal transportation considered, types of causal relations considered, variable classifications, stock and flow diagram elements, and sensitivity and scenario analysis considerations.

Most relevant literature on maritime transportation focuses on coastal container ports studies. For example, Luo and Grigalunas (2003) developed a simulation model to study fourteen large-scale, multimodal container ports in the United States in order to estimate port demands based on price elasticity of demand and port fees. Luo and Grigalunas (2003) emphasized on the importance of tradeoff between the transportation cost and costs associated with transportation duration. De and Ghoshb (2003) studied the relationship between port traffic and port performance for ports in India. The authors utilized unit root and causality tests and found that better port performance leads to higher port traffic. Fagerholt et al. (2010) combined a Monte Carlo simulation with an optimization model to develop a decision support tool for a Norwegian shipping company. More detailed literature review of operations research studies for the container terminals are discussed by Stahlbock and Voß (2008) and Steenken et al. (2004).

One focus of the NIW relevant literature concentrates on lock/dam performance (Melody & Schonfeld, 1993; Kim & Schonfeld, 1995; Ramanathan & Schonfeld, 1994; Melody & Schonfeld, 1998). For example, discrete-event simulation is applied to deduce the impacts of infrastructure improvements on inland waterway traffic congestion (Smith et al., 2009). A five lock section of the Upper Mississippi River is presented by Smith et al. (2009) as a case study. Grigalunas et al. (2001) used a simulation model and genetic algorithm to schedule lock/dam investment projects over a multi-year study time horizon. By using a Monte Carlo simulation model, a 10-lock segment of the Illinois and Upper Mississippi River is studied by Carroll and Bronzini (1973) to examine shipments move through ports and locks/dams and calculate costs due to time spent in the system. Another related area of NIW literature focusing on channel deepening projects. For instance, Almaz and Altiok (2012) studied the impact of channel deepening on port utilization and port processing time. An illustrative case study on Delaware River was presented in this study. The result of Carroll and Bronzini (1973) illustrated that limited benefits can be obtained from channel deepening projects, and dry bulk and general cargo commodities do not benefit from deepening projects significantly. Grigalunas et al. (2005) study channel deepening projects and who benefits most from these projects. The economic measures considered by Grigalunas et al. (2005) are transportation costs, gains to suppliers of port-related services, and environmental costs, and they study the deepening of the Delaware River. Based on a fifty year study, they measure a 5.875 percent net benefit as a result of deepening the Delaware River.

In summary, the literature review indicates that limited attention has been given to the measurement of the economic impacts that inland waterway transportation systems under the real world scenarios such as investment, potential disruption, and demand change scenarios. Likewise, most scholars did not account for indirect and induced impacts and strictly focused on initial cost-benefit benefits.

5.3 Methodology

To measure the economic impacts of the navigable inland waterway transportation system, eight scenarios are studied in this research. These real world scenarios are a base scenario of normal operations, channel deepening, port expansion, lock/dam rehabilitation, system-wide investment, lock/dam scheduled and unscheduled unavailabilities, and demand change due to the Panama Canal Expansion scenarios. The MarTranS developed by Oztanriseven and Nachtmann (2016) is utilized to model and measure these economic impacts.

A primary strength of MarTranS is that it enables users to model an inland waterway transportation system at the operational and system level. Moreover, the modular structure of MarTranS provides flexibility to change model parameters and allow users to conduct scenario analyses without any difficulty. By utilizing MarTranS, our study fills a gap in evaluating and understanding the economic impacts of potential real world inland waterway transportation scenarios and allows the study of interdependent relationships between NIW transportation infrastructures and associated economic impacts. Understanding these real world impacts will allow maritime stakeholders to allocate available funding more effectively within the decision alternatives.

5.3.1 MarTranS Structure

MarTranS structure (Oztanriseven & Nachtmann, 2016) is presented in Figure 2. There are three main components of MarTranS, namely agent-based modeling, discrete-event simulation, and system dynamics. Moreover, MarTranS is integrated with a multiregional input-output model to measure the total economic impact as the summation of direct, indirect, and induced economic impacts. Each simulation sub-model is used for a specific purpose to benefit from its strengths. First, the MarTranS discrete-event simulation sub-model is utilized to model operational level activities, such as commodity arrivals, navigation on the inland waterway, port handling processes, and lock/dam operations. Second, the MarTranS agent-based sub-model stores important information about each agent. Each shipment of the four types of commodities (dry cargo, dry bulk, liquid bulk, and grain) and the three modes of transportation (NIW, rail, and highway) is defined as an agent. The information collected with respect to these agents are shipment capacity, system entry and exit times, type of commodity, current stage of shipment, and number of shipments. In addition, a function is defined for each type of agent to route the agent between the assigned ports and locks/dams based on historical probabilities. Furthermore, the stored information with respect to the agents by the agent-based modeling is used to link the discrete-event simulation and the system dynamics sub-models.

Lastly, the MarTranS system dynamics sub-model translates the collected information of number of shipments, time spent in the system, and distance traveled into transportation, holding, and penalty costs to calculate the commodity prices every year. These commodity prices are then used to calculate the next year’s demands and last year’s economic impacts. The multiregional input-output model utilizes economic impact multipliers to calculate the economic impacts in terms of sales, GDP, tax, and employment.

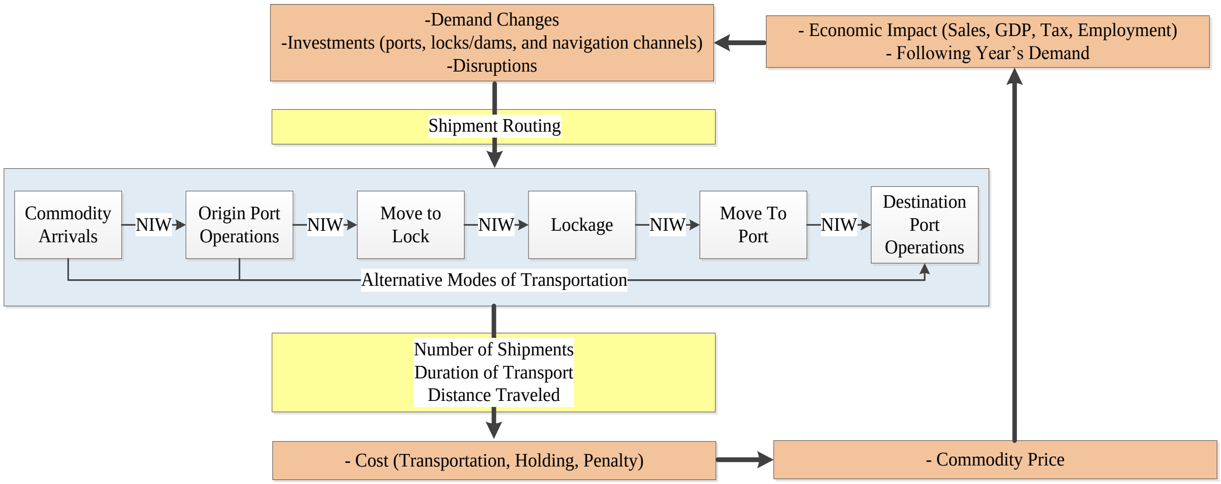

Figure 2 MarTranS Structure (Oztanriseven & Nachtmann, 2016)

5.3.2 Model Formulation

A detailed explanation of the design and structure of the model formulation utilized in MarTranS is presented by Oztanriseven and Nachtmann (2016). To conduct scenario analyses, certain MarTranS equations are updated depending on the scenario under study and a thorough explanation of these modifications is discussed in this section. The notations for sets, parameters, and equations are illustrated as follows.

	Sets
$i \epsilon I$	Set of commodities
$t \epsilon T$	Set of years
$q \epsilon Q$	Set of transportation modes *q* = {1: water, 2: rail, 3: truck, 4: other}

	Parameters
$\bar{\lambda}_i^q(t)$	Average number of commodity *i* shipments by mode of transportation *q* per day in year *t*
$f_i^q(t)$	Flow of commodity *i* by mode of transportation *q* in tons in year *t*
$\Gamma_i^q(t)$	Capacity of mode of transportation *q* in tons for commodity *i* in year *t*
$B_i(t)$	Capacity of barge carrying commodity *i* by in year *t*
$N_i(t)$	Number of barges per shipment in year *t*
$\Theta\ (t)$	Number of NIW working days in year *t*
$\beta_i(t)$	Commodity *i*NIW demand growth rate due to the impact of Panama Canal Expansion in year *t*

$\xi_i(t)$ Shipment capacity increase rate due to channel deepening in tons for commodity *i* in year *t*

Model (Modified Equations)

$$\bar{\lambda}_i^q(t) = (1 + \beta_i(t))\left(\frac{f_i^q(t)}{\Gamma_i^q(t)\ \Theta(t)}\right) \quad \forall i \epsilon \mathrm{I}; \forall q \epsilon \mathrm{Q}; \forall \mathrm{t} \epsilon \mathrm{T} \qquad \textbf{(1)}$$

$$\Gamma_i^1(t) = \xi_i(t) B_i(t)\ N_i(t) \qquad \forall i \epsilon \mathrm{I}; \forall \mathrm{t} \epsilon \mathrm{T} \qquad \textbf{(2)}$$

To measure the economic impacts of the inland waterways transportation system, MarTranS's Equation 1 and Equation 2 are updated. Equation 1 is modified by adding, $(\mathbf{1} + \boldsymbol{\beta}_{\boldsymbol{i}}(\boldsymbol{t}))$ to the $\bar{\boldsymbol{\lambda}}_{\boldsymbol{i}}^{\boldsymbol{q}}(\boldsymbol{t})$ equation to account for the demand change every year. In other words, the demand of each commodity via NIW is updated based on the growth rate impact due to the Panama Canal Expansion. Moreover, Equation 2 is modified by adding $\boldsymbol{\xi}_{\boldsymbol{i}}(\boldsymbol{t})$ to update $\boldsymbol{B}_{\boldsymbol{i}}(\boldsymbol{t})$ to calculate the new $\boldsymbol{\Gamma}_{\boldsymbol{i}}^{\mathbf{1}}(\boldsymbol{t})$ to account for the capacity increase due to channel deepening. This capacity increase occurs because the deepening of the navigation channel can accommodate barges that can withhold more tonnage.

5.4 Case Study: McClellan-Kerr Arkansas River Navigation System

To demonstrate the applicability of MarTranS, the McClellan-Kerr Arkansas River Navigation System (MKARNS) is utilized as the case study region for this research. The first step in this study is to simulate normal operations "base scenario". The base scenario is used as a comparison reference for the other seven real world scenarios studied.

The MKARNS consists of 440 miles of navigation channel (Tulsa Port of Catoosa, 2016) that connects Oklahoma, Arkansas, and the surrounding states with the rest of the world by providing a fuel-efficient and an environment-friendly mode of transportation (ODOT, 2015). Furthermore, several ancillary benefits are provided by the MKARNS. These benefits are habitats for endangered and threatened species, flood protection, hydropower energy generation, and recreation (ODOT, 2015). However, similar to many inland waterways in the U.S., due to a lack of available funding, the MKARNS suffers from limited investment in the aging infrastructures (AOPOA, 2012). A description of the data sources can be found in Oztanriseven and Nachtmann (2016).

5.5 Results

The results of the real world scenario analyses conducted via MarTranS to examine economic impacts of the inland waterway transportation system are discussed in this section. A study period of fifty years is selected to account for the long-term impacts that the selected real world scenarios have on the MKARNS performance. In this study, commodities are grouped into four categories (dry cargo, dry bulk, liquid bulk, and grain) and are considered in each of the scenarios. The commodity group of dry cargo is comprised of iron and steel and manufacturing equipment and machinery. The dry bulk commodity group includes chemical fertilizer, coal and coke, sand/gravel and rock, and minerals and building materials. The liquid bulk commodity group includes other chemicals and petroleum products. Lastly, the grain commodity group includes wheat, soybeans, and food/farm products. For the purpose of this study, six performance measures (sales, GDP, tax, employment, commodity flow, and port utilization) for each scenario are evaluated against performance of the base scenario. These results are compared to evaluate the economic impacts of each real world scenario has on future MKARNS performance. AnyLogic 7.3 software was utilized to obtain these results and to run the simulation model.

5.5.1 Base Scenario

The base scenario conducted by Oztanriseven and Nachtmann (2016) is utilized to evaluate and compare the economic impacts of the other seven real world scenarios. In the base scenario, it is assumed that the lock/dam disruptions, due to scheduled and unscheduled unavailabilities, will continue throughout the entire time frame of the study. These disruption behaviors are based on the trends observed in the historical disruption records. Also, it is assumed that the Panama Canal Expansion will have no impact on the MKARNS, and no investments will take place in the MKARNS infrastructures such as ports, locks/dams, and the navigation channel.

As a result of the base scenario, the GDP impacts are illustrated in Figure 3 for the study period. It is observed that total GDP impact increases from $7 billion to $8.7 billion from 2016 to 2022. However, an interesting observation is that from 2022 forward, the total GDP impact collapses to $1 billion. This collapse can be attributed to the inland waterway transportation system's congestion due to the lack of investment in the MKARNS infrastructures.

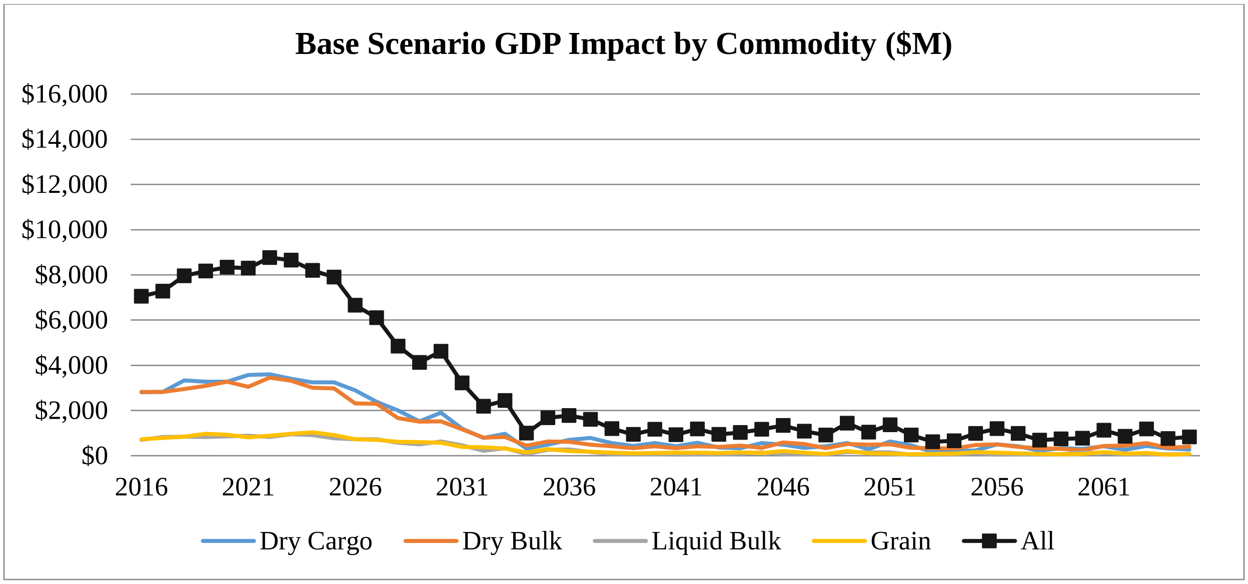

Figure 3 Base Scenario GDP Impact by Commodity

Table 1 presents the results of the six selected performance measures. It can be observed that the net present value (NPV) of sales, GDP, and tax economic impacts are $232.5 billion, $111.3 billion, and $7.8 billion respectively for the fifty year study period. Correspondingly, on average, 36,012 jobs were generated every year directly or indirectly due to maritime activities related to the MKARNS. From the simulation results, it can be inferred that approximately eighty percent of these economic impacts are generated due to dry cargo and dry bulk commodities. However, the top two commodities in terms of tonnage flow are dry bulk and liquid bulk commodities which account for seventy-seven percent of the whole of MKARNS' traffic. It is also observed that average port utilizations vary between forty-five percent for dry bulk to eighty-one percent for liquid bulk. The summation of transportation, holding, and penalty costs per ton is between $55.05 to $59.01. These costs refer to five percent to twenty-seven percent of the commodity prices per ton. Since commodity flows change dramatically due the effect of MKARNS' congestion, a high deviation of coefficients of variation around a hundred percent exists for all commodities in terms of the four economic indicators (sales, GDP, tax, and employment) as well as commodity flows in tons. These high deviations result in low predictability of future forecasts.

Table 1 Base Scenario Performance Measures by Commodity

		NPV Sales ($M)	NPV GDP ($M)	NPV Tax ($M)	Emp. (#Jobs)	Flow (ton/year)	Port Util.
Dry Cargo	**Mean**	$86,846	$44,722	$2,922	$14,412	559,352	68%
Dry Bulk	**Mean**	$89,963	$41,999	$3,505	$13,666	2,587,032	45%
Liquid Bulk	**Mean**	$26,820	$11,854	$600	$3,794	497,872	81%
Grain	**Mean**	$28,895	$12,738	$776	$4,140	1,046,320	72%
All	**Mean**	$232,525	$111,313	$7,803	$36,012	4,690,576	53%

5.5.2 Investment Scenarios

The base scenario demonstrated that MKARNS' economic impacts increase during the first seven years, but this growth cannot be sustained for a longer time frame. This result motivated our study to investigate possible investment scenarios to analyze and compare the associated economic outcomes. To better understand these economic outcomes of these four investment scenarios, three hypotheses were developed. These hypotheses are: 1) Investments in the current bottlenecks (primary sources of system delays) in the NIW system will increase the system's economic impacts. 2) Investment in non-bottleneck components will not result in the same level of increase as investment in bottleneck infrastructure, 3) Investing in a combination of system components will generate a greater economic impact than investing in each individual component due to the nonlinear relationships between the system components,

Four investment scenarios are considered in this section. The first scenario is to invest in the navigation channel to increase the channel depth from nine feet to twelve feet (9' to 12'). This investment strategy was approved by Congress in 2004, but it has not been completed because of a lack of funding (ODOT, 2013). The cost of deepening the MKARNS is estimated to be $183 million (USACE, 2013). The second investment scenario is to invest in the congested ports. In this study, a dock in a port is considered congested if it exceeds eighty percent utilization rate in the base scenario. The third investment scenario is to invest in critical locks/dams. A lock/dam is defined as critical if its utilization rate exceeds eighty percent. The fourth and last investment scenario is to invest in all inland waterway transportation system infrastructure options including the navigation channel, congested ports, and critical locks/dams.

5.5.2.1 Channel Deepening Investment Scenario

The channel deepening investment scenario differs from the base scenario in terms of the depth of the navigation channel which increases from nine to twelve feet (9’ to 12’). This increase in the channel depth will allow a barge to carry an extra 600 tons (ODOT, 2015).

It is observed in Figure 4 that the total GDP impact increases from $7 billion in 2016 to $9.4 billion in 2023. However, the GDP impact decreases drastically from 2023 until 2032 from $9.4 billion to $2 billion due to the lock/dam congestions. Then, for the next 20 years, the reduction of the GDP impact gradually slows down. After year 2052, the GDP impact starts to oscillate around $1 billion. The outcome of the channel deepening investment scenario shows that the results behave as predicted in our second hypothesis which is investments in non-bottleneck infrastructures will not yield the same level of economic impact as in investments in bottleneck system infrastructures. Since the GDP impact did not increase significantly due to the investment in the MKARNS navigation channel, it can be concluded that the navigation channel is not the bottleneck in the MKARNS.

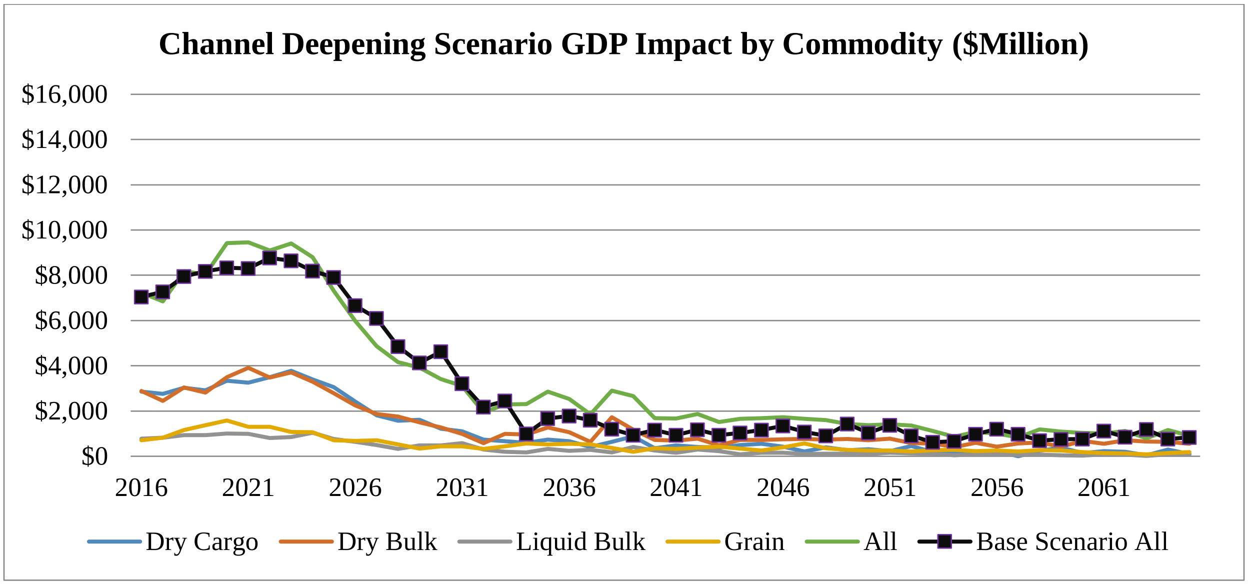

Figure 4 Channel Deepening Scenario GDP Impact by Commodity

The performance measures for the channel deepening scenario can be found in Table 2. Net present value of sales, GDP, and tax economic impacts are $247.8 billion, $118.6 billion, and $8.3 billion respectively for the fifty year time frame. The economic impact of the channel deepening investment scenario is seven percent higher than the base scenario. Another noteworthy result is that grain commodities benefit in the channel deepening investment scenario more than the other commodities, showing a thirty-six percent improvement on the economic impact over the base scenario. Another remarkable result of the channel deepening investment scenario is that dry cargo commodities have slightly less economic impact over the base scenario since the MKARNS efficiencies led to higher demands for other commodities which resulted in system congestion. Therefore, limited improvement in the economic indicators leads to an argument of whether investments in the bottleneck infrastructures should be the priority.

Table 2 Channel Deepening Scenario Performance Measures

		NPV Sales ($M)	**NPV GDP ($M)**	**NPV Tax ($M)**	**Emp. (# Jobs)**	**Flow (ton/year)**	**Port Util.**
Dry Cargo	**Mean**	$80,746	$41,581	$2,717	$13,400	558,256	64%
	Difference	-7%	-7%	-7%	-7%	0%	-4%
Dry Bulk	**Mean**	$100,987	$47,145	$3,934	$15,340	3,245,232	57%
	Difference	12%	12%	12%	12%	25%	12%
Liquid Bulk	**Mean**	$28,513	$12,602	$638	$4,033	581,872	94%
	Difference	6%	6%	6%	6%	17%	13%
Grain	**Mean**	$39,268	$17,311	$1,055	$5,627	1,516,344	97%
	Difference	36%	36%	36%	36%	45%	24%
All	**Mean**	$247,829	$118,639	$8,317	$38,382	5,901,704	66%
	Difference	7%	7%	7%	7%	26%	13%

5.5.2.2 Port Investment Scenario

In this scenario, investment in the seventeen docks with a utilization rate of eighty percent or higher occurs. Five of these docks correspond to dry cargo, six of them to liquid bulk, and six of them to grain commodities. Since the dry bulk docks in the MKARNS did not exceed eighty percent utilization rate, investment in these docks did not take place. The invested docks are dry cargo: 1) Tulsa Port of Catoosa, 2) Johnston's Port 33, 3) Port of Muskogee, 4) Port of Fort Smith and Five Rivers Distribution, and 5) Port of Pine Bluff; liquid bulk: 1) Tulsa Port of Catoosa, 2) Johnston's Port 33, 3) Port of Muskogee, 4) Port of Dardanelle (Oakley), 5) Port of Little Rock, and 6) Port of Pine Bluff; and grain: 1) Tulsa Port of Catoosa, 2) Johnston's Port 33, 3) Port of Muskogee, 4) Port of Keota, 5) Port of Dardanelle (Oakley), 6) Port of Pine Bluff.

The capacity of congested docks was increased by doubling their current capacities. The costs of these expansion projects for each ton per day of cargo handling capacity were calculated based on the past port investments and commodity flows. These costs are associated with expenditures of structure and equipment and calculated as $25.91 for dry cargo, $25.71 for liquid bulk, and $33.75 for grain dock. Therefore, the annual total cost for these port expansion investments is calculated to be $569.9 million. The breakdown of this total expenditure is $51.4 million for dry cargo docks, $69 million for liquid bulk docks, and $449.4 million for the grain docks.

The results of the port investment scenario in Figure 5 showed that the total GDP impact increases from $7 billion in 2016 to $9.9 billion in 2019. Until 2022, the total GDP impact stayed right below $10 billion. However, the GDP impact starts to decline and reaches an equilibrium point of $1 billion in 2036. A slight improvement in the GDP impact of the MKARNS is observed, but it can be deduced from the analysis that this improvement could not be sustained after the year 2022.

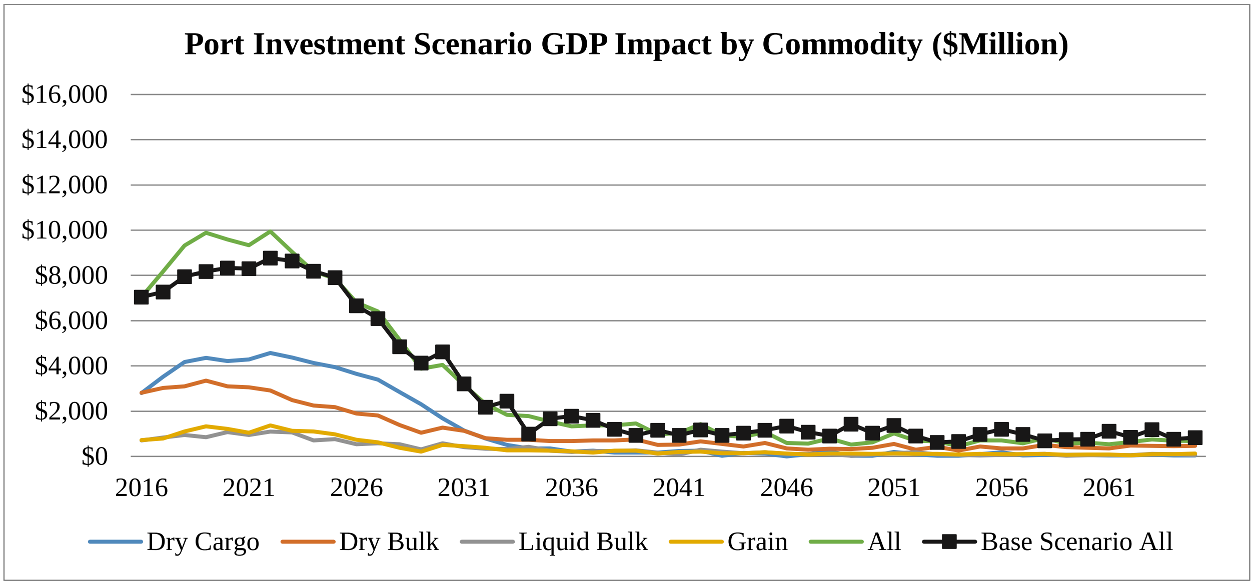

Figure 5 Port Investment Scenario GDP Impact by Commodity

A detailed analysis of all the six performance measures is illustrated in Table 3. Net present value of sales, GDP, and tax economic impacts are $241.8 billion, $115.8 billion, and $8.1 billion respectively for the fifty year study period. These economic indicator values resulted in a four percent improvement over the base scenario as predicted in the second hypothesis. It is interesting to observe that the expansion on dry cargo, liquid bulk, and grain docks led to a higher economic impact of these commodities. However, the increase in flow of these three commodities caused a congestion in the MKARNS which then resulted in a decrease in the economic impact and flow of dry bulk commodities. Another noteworthy remark is that, while the average flow increased by two percent in this scenario, the average port utilization decreased by twenty-two percent due to the expanded port capacities. In summary, very limited improvement of sales impact by $186.6 million every year over the base scenario makes the port expansion investments of $569.9 million every year, an unfavorable decision.

Table 3 Port Investment Scenario Performance Measures

		NPV Sales ($M)	NPV GDP ($M)	NPV Tax ($M)	Emp. (# Jobs)	Flow (ton/year)	Port Util.
Dry Cargo	**Mean**	$95,756	$49,310	$3,222	$15,890	596,240	36%
	Difference	10%	10%	10%	10%	7%	-32%
Dry Bulk	**Mean**	$84,744	$39,562	$3,301	$12,873	2,544,344	42%
	Difference	-6%	-6%	-6%	-6%	-2%	-4%
Liquid Bulk	**Mean**	$28,777	$12,719	$644	$4,070	544,040	55%
	Difference	7%	7%	7%	7%	9%	-26%
Grain	**Mean**	$32,186	$14,189	$865	$4,612	1,092,024	46%
	Difference	11%	11%	11%	11%	4%	-27%
All	**Mean**	$241,857	$115,780	$8,116	$37,457	4,776,648	32%
	Difference	4%	4%	4%	4%	2%	-22%

5.5.2.3 Lock/Dam Investment Scenario

The results of the channel deepening investment and port investment scenarios indicate that only limited improvement in the economic indicators can be attained. Moreover, the lack of funding on the lock/dam infrastructure is considered the biggest threat for the inland waterway transportation system (ASCE, 2013). To understand whether the MKARNS locks/dams are the bottlenecks in the system, a lock/dam investment scenario is conducted. In this scenario, the critical locks/dams are selected as the investment options. A lock/dam is defined as critical if it has greater than an eighty percent utilization rate in the base scenario. The congested locks/dams are: Lock 22, Lock 13, Lock 10, Lock 5, and Lock 2. These congested locks/dams are the only ones considered for rehabilitation investments costing on average $30 million per lock/dam. Therefore, the total cost of rehabilitation investment in these five congested locks/dams is approximately $150 million (IMTS, 2010). We did not consider a new lock/dam construction option due to the high investment costs ranging from $120 million to $240 million (IMTS, 2010). Moreover, studies show that the life of a lock/dam can be extended by twenty-five years with major rehabilitation (IMTS, 2010). Consequently, it is assumed in our study that by investing in lock/dam rehabilitation, the lock/dam scheduled and unscheduled unavailabilities will be reduced by 100 percent in the first year with no reduction at the end of the twenty-fifth year assuming that the reduction decreases linearly every year.

In the lock/dam investment scenario as illustrated in Figure 6, the total GDP impact increased from $7 billion in 2016 to $10.6 billion in 2028. It is observed that, from 2028 to 2045, the GDP impact decreased to an equilibrium value of $600 million. Hence, it is discerned that investing in these five critical locks/dams increased the life of the MKARNS by more than a decade. Furthermore, investing in the construction of new locks/dams should be considered in order to have a sustainable MKARNS system.

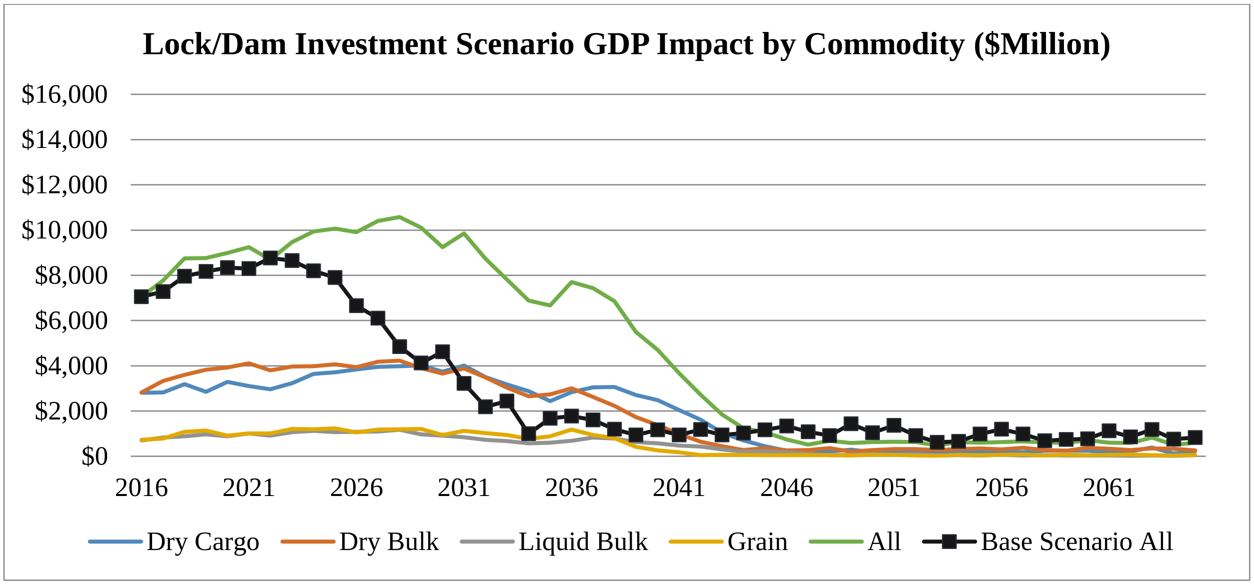

Figure 6 Lock/Dam Investment Scenario GDP Impact by Commodity

As analyzed, the lock/dam investment scenario generated the highest GDP impact in comparison with the base scenario along with the channel deepening investment and port investment scenarios. Table 4 captures the performance measures for the lock/dam investment scenario. The performance measures of net present value of sales, GDP, and tax economic impacts are $354.8 billion, $169.8 billion, and $11.9 billion respectively for the fifty year study period. These results are fifty-three percent higher than the corresponding values in the base scenario as stated in the first hypothesis. By investing $150 million in the five congested locks/dams, the MKARNS would directly or indirectly generate $1.1 billion of GDP impact annually.

Table 4 Lock/Dam Investment Scenario Performance Measures

		NPV Sales ($M)	NPV GDP ($M)	NPV Tax ($M)	Emp. (# Jobs)	Flow (ton/year)	Port Util.
Dry Cargo	**Mean**	$126,982	$65,390	$4,272	$21,072	866,984	87%
	Difference	46%	46%	46%	46%	55%	19%
Dry Bulk	**Mean**	$145,434	$67,895	$5,666	$22,092	4,152,800	81%
	Difference	62%	62%	62%	62%	61%	35%
Liquid Bulk	**Mean**	$39,969	$17,665	$894	$5,653	788,336	90%
	Difference	49%	49%	49%	49%	58%	9%
Grain	**Mean**	$42,867	$18,897	$1,152	$6,142	1,570,640	86%
	Difference	48%	48%	48%	48%	50%	14%
All	**Mean**	$354,801	$169,848	$11,907	$54,949	7,378,760	80%
	Difference	53%	53%	53%	53%	57%	26%

5.5.2.4 System-wide Investment Scenario

The observed increase of the average port utilization by twenty-six percent as a result of the lock/dam investment scenario suggests a reconsideration of investments in both the navigation channel and congested ports along with the lock/dam investment. Therefore, it was determined that running a scenario analysis to measure the economic impact of the MKARNS based on the investments in all inland waterway infrastructures including the deepening the navigation channel, the seventeen congested docks, and the five congested locks/dams would be informative. As explained earlier, these investment scenarios increased the total GDP impact by seven percent, four percent, and fifty-three percent respectively.

As a result of running the system-wide investment scenario, it was observed in Figure 7 that the total GDP impact increased from $7 billion in 2016 to $13.6 billion in 2024. Although the GDP impact fluctuated between the years 2024 and 2031, the MKARNS still could sustain this level of GDP impact over these seven years. However, after 2031, the MKARNS GDP impact experienced a decline similar to the other investment scenarios up until 2043 and later on started to oscillate around $1 billion.

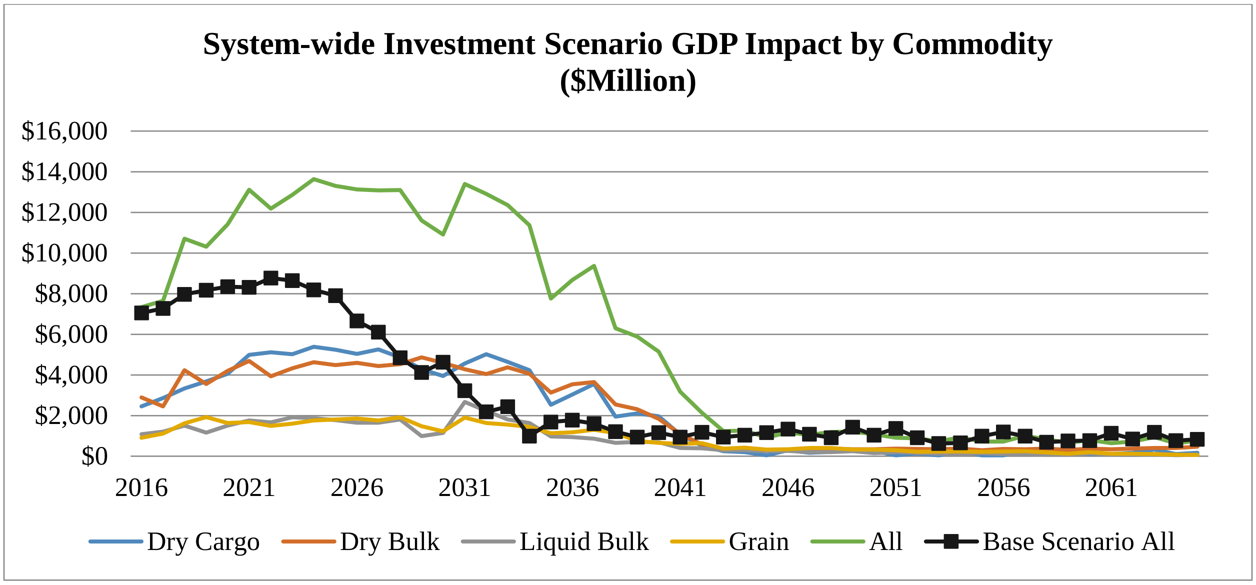

Figure 7 System-wide Investment Scenario GDP Impact by Commodity

As predicted in the third hypothesis, the system-wide investment scenario resulted in the highest economic impact in comparison to the other investment scenarios. The system-wide investment scenario generated ninety-two percent higher value in the four economic indicators, which is in fact greater than the sum of the individual investment scenarios: channel deepening, port investments, and lock/dam investments, which interestingly was a sixty-four percent improvement in comparison to the base scenario. Table 5 summarizes the performance measures for the system-wide investment scenario. It can also be observed from the analysis that the net present value of sales, GDP, and tax economic impacts are $445.8 billion, $213.4 billion, and $15.0 billion respectively for the fifty year study period.

Table 5 System-wide Investment Scenario Performance Measures

		NPV Sales ($M)	NPV GDP ($M)	NPV Tax ($M)	Emp. (#Jobs)	Flow (ton/year)	Port Util.
Dry Cargo	**Mean**	$150,069	$77,279	$5,049	$24,904	806,432	76%
	Difference	73%	73%	73%	73%	44%	8%
Dry Bulk	**Mean**	$163,700	$76,423	$6,377	$24,866	4,214,976	76%
	Difference	82%	82%	82%	82%	63%	30%
Liquid Bulk	**Mean**	$65,762	$29,065	$1,472	$9,302	918,488	87%
	Difference	145%	145%	145%	145%	84%	6%
Grain	**Mean**	$69,471	$30,625	$1,867	$9,955	1,878,040	95%
	Difference	140%	140%	140%	140%	79%	22%
All	**Mean**	$445,762	$213,392	$14,959	$69,036	7,817,936	74%
	Difference	92%	92%	92%	92%	67%	20%

5.5.3 Disruption Scenarios

The lock delays for the Arkansas and Red River Basin reached a critical level and received an F grade from America's Watershed Initiative (AWI) which consists of hundreds of experts from the thirty-one states containing the Mississippi River Watershed (AWI, 2015). Furthermore, the lock/dam investment scenario in this study illustrated earlier that without investing in the critical lock/dam infrastructures, the MKARNS system cannot generate a sustainable economic impact. Therefore, in this section, we examine the lock/dam disruptions and their potential economic impacts. The lock/dam scheduled and unscheduled unavailability disruptions are considered in this study based on the data provided by USACE (2015). We conducted a regression analysis and probability distribution fitting to scheduled and unscheduled unavailabilities (USACE, 2015) for each of the eighteen locks/dams located in the MKARNS. These results are then utilized as input parameters in MarTranS to generate the number of scheduled and unscheduled unavailabilities and the duration of each of these unavailabilities every year.

5.5.3.1 Lock/Dam Scheduled Unavailability Disruption Scenario

To measure the economic loss incurred due to the planned unavailabilities, all the planned unavailabilities from MarTranS were eliminated to measure their corresponding economic impact. Thus, the difference between the economic impact of the base scenario and the lock/dam scheduled unavailability disruption scenario will show the economic losses due to scheduled unavailability disruptions.

In the lock/dam scheduled unavailability disruption scenario, Figure 8, the total GDP impact increased from $7 billion in 2016 to $10.6 billion in 2026. After 2026, the GDP impact declined until 2051 and from then on it oscillated around $2 billion. In comparison to the base scenario, the increase trend lasted longer, and the system reached an equilibrium in GDP impact of approximately two times higher than that of the base scenario; $2 billion versus $1 billion.

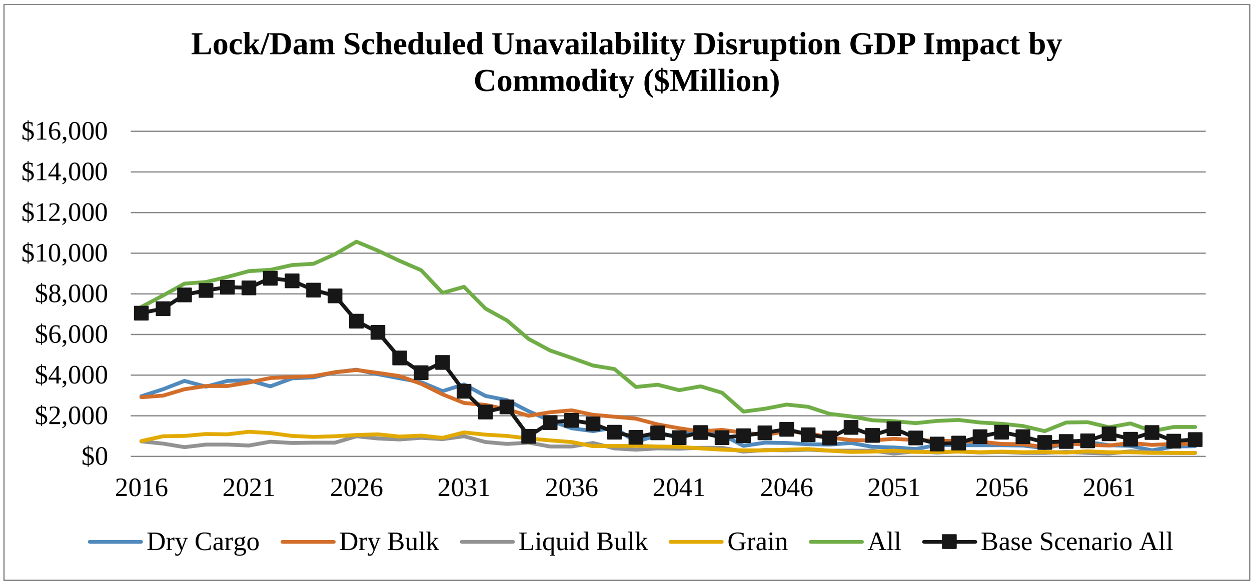

Figure 8 Lock/Dam Scheduled Unavailability Disruption GDP Impact by Commodity

The results of the lock/dam scheduled unavailability disruption scenario are given in Table 6. It can be observed from the results that the net present value of sales, GDP, and tax economic impacts are $349.2 billion, $167.1 billion, and $11.7 billion respectively. Therefore, we conclude that annual sales, GDP, tax, and employment economic impacts of the lock/dam scheduled unavailability disruption scenario are $2.3 billion, $1.1 billion, $78 million, and 18,063 jobs respectively. As predicted in the fourth hypothesis, values of the four economic indicators increased by fifty percent over the base scenario. Grain commodities benefited the most with sixty percent improvement, and liquid bulk commodities experienced the least improvement of twenty-seven percent.

Table 6 Lock/Dam Scheduled Unavailability Disruption Scenario Performance Measures

		NPV Sales ($M)	NPV GDP ($M)	NPV Tax ($M)	Emp. (# Jobs)	Flow (ton/year)	Port Util.
Dry Cargo	**Mean**	$125,094	$64,418	$4,209	$20,759	824,992	89%
	Difference	44%	44%	44%	44%	47%	21%
Dry Bulk	**Mean**	$144,356	$67,392	$5,624	$21,928	3,364,000	72%
	Difference	60%	60%	60%	60%	30%	26%
Liquid Bulk	**Mean**	$33,974	$15,016	$760	$4,805	710,384	96%
	Difference	27%	27%	27%	27%	43%	15%
Grain	**Mean**	$46,094	$20,320	$1,238	$6,605	1,755,544	89%
	Difference	60%	60%	60%	60%	68%	17%
All	**Mean**	$349,156	$167,146	$11,717	$54,074	6,654,920	76%
	Difference	50%	50%	50%	50%	42%	23%

5.5.3.2 Lock/Dam Unscheduled Unavailability Disruption Scenario

The unscheduled delays impacting the U.S. inland waterways system has increased drastically. For example, in 2011, barges experienced the highest delays in the last twenty-five years, and ninety percent of locks/dams in the United States were disrupted by unscheduled failures (ASCE, 2013). Therefore, understanding the economic importance of these lock/dam failures is crucial for our society.

In the lock/dam unscheduled unavailability disruption scenario, Figure 9, it can be observed that the total GDP impact fluctuates between $7 billion and $8 billion from the years 2016 to 2029. After 2029, the GDP impact falls until 2047 and oscillates around $2 billion, similar to the lock/dam scheduled unavailability disruption scenario.

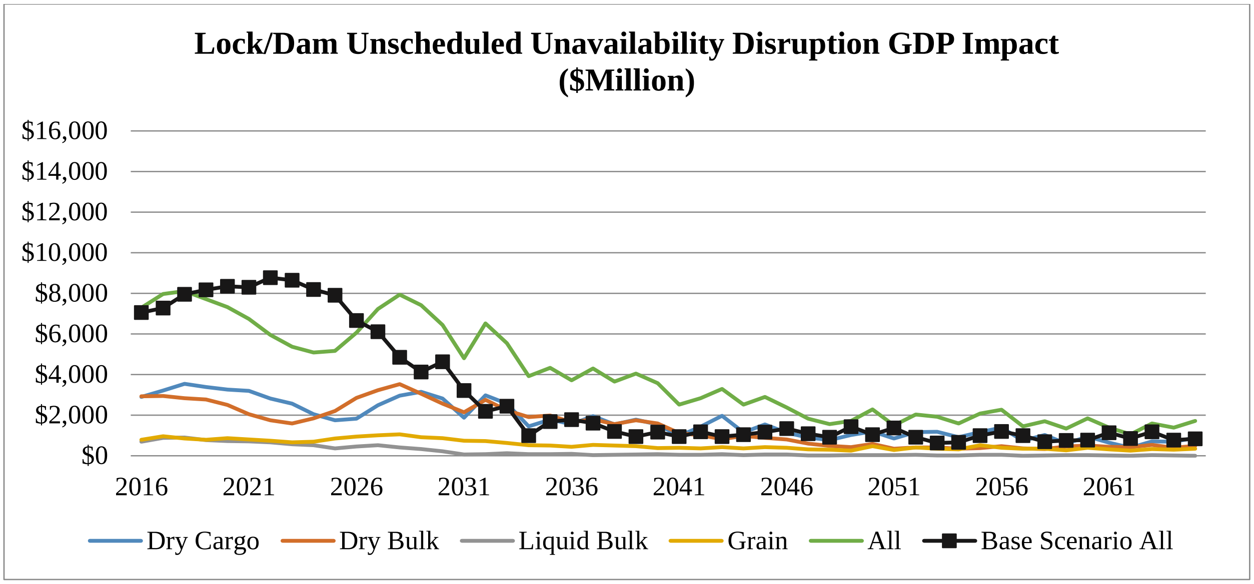

Figure 9 Lock/Dam Unscheduled Unavailability Disruption Scenario GDP Impact

The performance measures of the lock/dam unscheduled unavailabilty disruption scenario are given in Table 7. Net present value of sales, GDP, and tax economic impacts are $278.6 billion, $133.4 billion, and $9.4 billion respectively. Hence, the annual sales, GDP, tax, and employment economic impacts of the lock/dam unscheduled unavailability disruptions of the MKARNS are $923 million, $442 million, $31 million, and 7,144 jobs respectively. These economic indicator values refer to an improvement of twenty percent in comparison to the base scenario as predicted in the fourth hypothesis. However, not all commodities benefit from this improvement. For example, liquid bulk commodities had thirty-one percent economic loss due to the congestion created by the increased commodity traffic of the other three types of commodities.

Table 7 Lock/Dam Unscheduled Unavailability Disruption Scenario Performance Measures

		NPV Sales ($M)	NPV GDP ($M)	NPV Tax ($M)	Emp. (# Jobs)	Flow (ton/year)	Port Util.
Dry Cargo	**Mean**	$112,040	$57,696	$3,770	$18,593	705,048	81%
	Difference	29%	29%	29%	29%	26%	12%
Dry Bulk	**Mean**	$107,149	$50,022	$4,174	$16,276	3,036,184	58%
	Difference	19%	19%	19%	19%	17%	12%
Liquid Bulk	**Mean**	$18,399	$8,132	$412	$2,602	390,920	66%
	Difference	-31%	-31%	-31%	-31%	-21%	-15%
Grain	**Mean**	$39,801	$17,546	$1,069	$5,703	1,411,720	85%
	Difference	38%	38%	38%	38%	35%	13%
All	**Mean**	$278,654	$133,395	$9,351	$43,156	5,543,872	62%
	Difference	20%	20%	20%	20%	18%	9%

5.5.4 Demand Change Scenario due to the Panama Canal Expansion

The last scenario studied is demand change, specifically related to the Panama Canal expansion. Since 1914, the Panama Canal has been a crucial element of the world trade, and it serves 14,000 vessels connecting 1,700 ports annually between over 160 countries (Pant et al., 2015). The Panama Canal expansion was scheduled to be completed in 2014 and is expected to double the current capacity of the canal (USACE, 2012). The completion date was then rescheduled for June 2016, and it is expected to be a game changer for transportation systems worldwide. The Panama Canal is a cost-effective route option for the trade between Asia and the United States and increasing the size of the canal may result in a higher usage of the Mississippi River System (CDM Smith, 2015). The economic impact of the Panama Canal expansion on the Mississippi River System depends on the preparedness of the system, and the USACE states that the cost-benefits gained from the canal expansion may be counteracted by the congestion effect in the inland waterway transportation system (CDM Smith, 2015).

The Panama Canal expansion scenario in this study differs from the base scenario in that the demand increases annually at a rate of three percent due to the canal expansion (USACE, 2008). All other variables are assumed to behave similarly to the aforementioned scenarios. After running the simulation under the Panama Canal expansion scenario, the impact on the GDP can be observed in Figure 10. The total GDP impact increases from $7 billion to $8.9 billion between the years 2016 and 2020. After the year 2020, the total GDP impact falls to $1 billion and then oscillates around $1 billion until the end of the study time frame due to MKARNS' congestion.

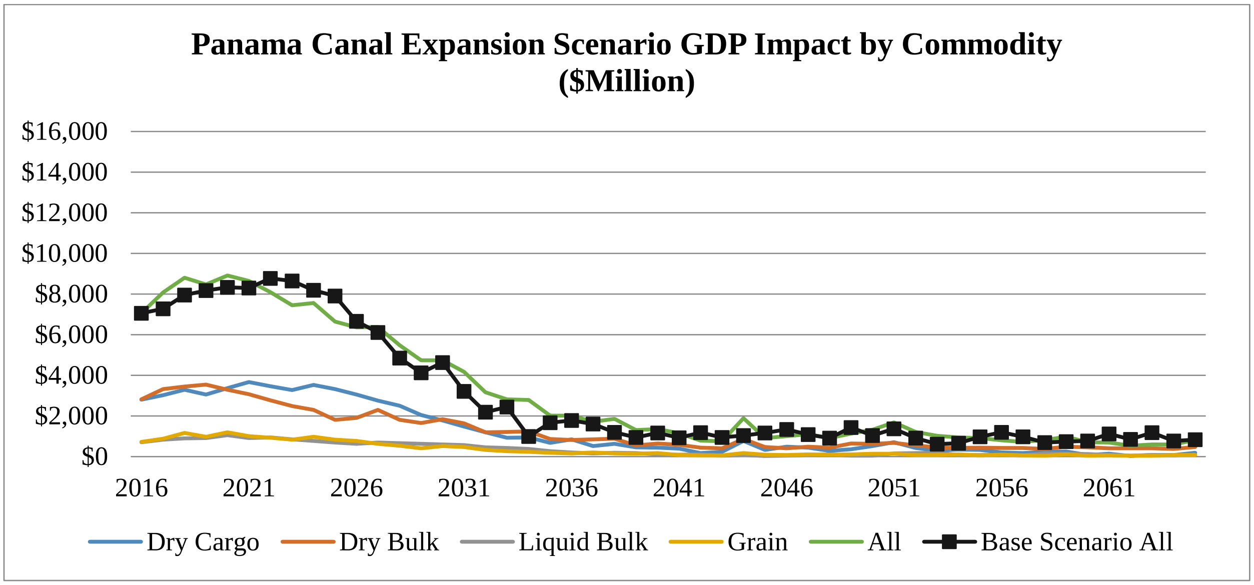

Figure 10 Panama Canal Expansion Scenario GDP Impact by Commodity

As presented in Figure 3 and Figure 10, the base scenario and the Panama Canal expansion scenario behave similarly in their economic impacts. This outcome was predicted in the fifth hypothesis. Table 8 summarizes the performance measures for the Panama Canal expansion scenario. Net present value of sales, GDP, and tax economic impacts are $241.2 billion, $115.5 billion, and $8.1 billion respectively for the fifty year study period. The economic impact of the Panama Canal Expansion is four percent higher than that of the base scenario for these four economic indicators. All four commodities benefit from the expansion similarly, between one percent and seven percent. It can be deduced from the comparison between the base scenario and demand change due to the Panama Canal expansion that the MKARNS generates slightly greater economic impacts with the expansion of the Panama Canal. Therefore, investing in the MKARNS infrastructure should be considered by the maritime transportation authorities in order to benefit more from the Panama Canal expansion.

Table 8 Panama Canal Expansion Scenario Performance Measures

		NPV Sales ($M)	NPV GDP ($M)	NPV Tax ($M)	Emp. (# Jobs)	Flow (ton/year)	Port Util.
Dry Cargo	**Mean**	$89,512	$46,095	$3,012	$14,854	603,768	73%
	Difference	3%	3%	3%	3%	8%	5%
Dry Bulk	**Mean**	$94,015	$43,890	$3,663	$14,281	3,006,720	57%
	Difference	5%	5%	5%	5%	16%	11%
Liquid Bulk	**Mean**	$28,622	$12,650	$641	$4,048	519,808	84%
	Difference	7%	7%	7%	7%	4%	3%
Grain	**Mean**	$29,072	$12,816	$781	$4,166	1,045,568	73%
	Difference	1%	1%	1%	1%	0%	1%
All	**Mean**	$241,170	$115,451	$8,093	$37,350	5,175,864	59%
	Difference	4%	4%	4%	4%	10%	6%

5.6 Case Discussion

Figure 11 illustrates the GDP impact of all eight scenarios conducted in this study. It is observed that the system-wide scenario generates the highest economic impact, followed by lock/dam investment, lock/dam scheduled unavailability disruption, and lock/dam unscheduled unavailability disruption scenarios in descending order. It can be inferred from the analysis that all scenarios result in a collapse of the GDP impact, but the system could operate longer when investments are made on the critical locks/dams. Therefore, it is concluded that in order to benefit from the MKARNS over a long period of time, necessary investments on critical infrastructure should take place by the MKARNS authorities, specifically aging locks/dams which are found to be the most critical investment options.

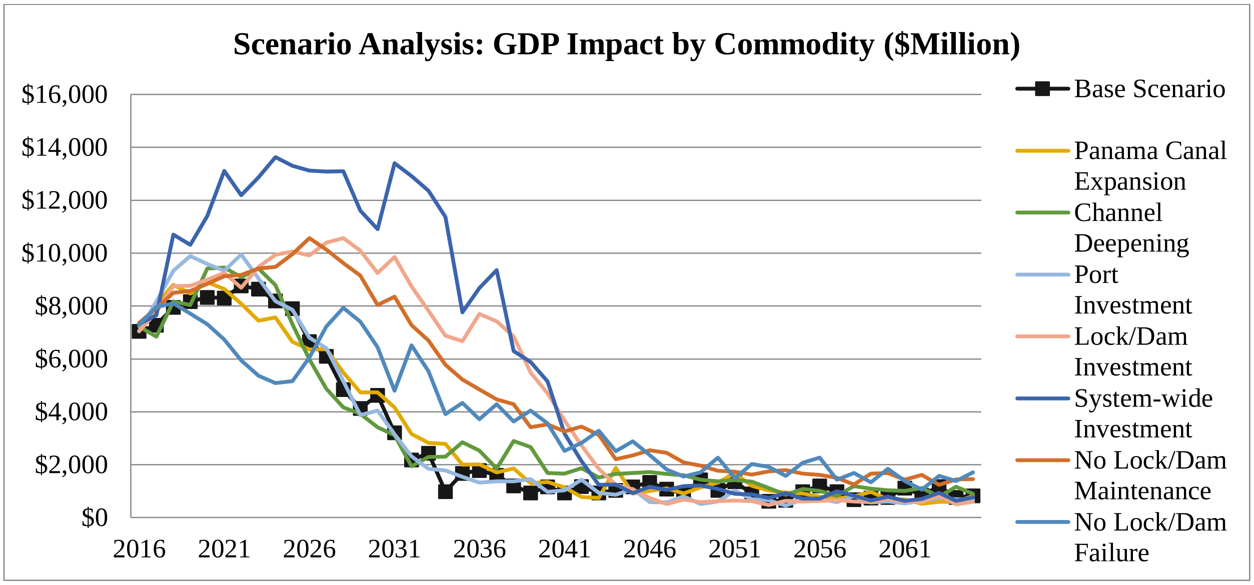

Figure 11 GDP Impact Scenario Comparisons

The main findings of our study are as follows.

- On average for all scenarios, seventy-seven percent of the economic impact is generated by dry cargo and dry bulk commodities, while seventy-eight percent of the flow is dry bulk and grain commodities. Therefore, the MKARNS authorities may want to invest more in the infrastructure involved with dry cargo and dry bulk commodities to improve the total economic benefits.

- If the MKARNS authorities do not invest in the critical locks/dams, the economic impacts generated will start to fall sometime between the years 2020-2023, and the economic impact will collapse by year 2032-2040. We observe that lock/dam rehabilitation investments can postpone the collapse by more than a decade. However, to have the MKARNS and its economic impact sustainable, new lock/dam investments may be considered due to the current age of locks/dams.
- Panama Canal expansion, channel deepening, and port investment decisions without investing in the critical locks/dams resulted in limited (4%-7%) improvement in the economic gains. The reason for this limited increase is that the system locks/dams are the bottlenecks. However, investing in the channel deepening, congested ports, and critical locks/dams together in the system-wide investment scenario generated the highest economic benefits. The system-wide investment scenario resulted in twenty-eight percent more than the sum of individual investment scenarios. Therefore, to increase total economic benefits, maritime authorities should consider investing system-wide if the available budget is adequate. Otherwise, they should prioritize investing in the critical locks/dams.
- Lastly, annual economic losses due to the lock/dam scheduled and unscheduled unavailabilities are $1.1 billion and $442 billion in GDP impact respectively. Therefore, as discussed earlier in the disruption scenarios section, investing in the critical locks/dams can reduce the negative economic impacts of the potential lock/dam disruptions.

5.7 Conclusions and Future Work

In this research, the economic impacts of eight different real world scenarios are studied, and the MKARNS is used to illustrate the applicability of the MarTranS to model these scenarios (Oztanriseven & Nachtmann, 2016). MarTranS consists of agent-based, discrete-event, and system dynamics simulation sub-models, and to measure the economic impacts of the real world inland waterway transport system scenarios, MarTranS is integrated with a multiregional input-output model. The results are presented in terms of sales, GDP, tax, and employment economic indicators. In addition, commodity flows and port utilizations are reported as two operational performance measures.

To the best of our knowledge, there is no research in relevant literature that discusses potential economic impacts of inland waterway transportation system under real world scenarios by utilizing a comprehensive multimethod simulation model. Moreover, understanding the relationships between the economic impacts of an inland waterway transportation system and the real world scenarios can increase the economic benefits and lead to a competitive advantage over other transportation systems. The conducted scenario analysis could be modified and utilized for any other inland waterway system such as the Mississippi, Rhine, Danube, Yangtze, and Rio de la Plata River Systems.

The results of the eight scenario analyses showed that dry cargo and dry bulk commodities generate the highest economic impact at seventy-seven percent of the total impact. However, the top two commodities in terms of flow are dry bulk and grain commodities, at seventy-eight percent of the total flow. Moreover, the locks/dams in the MKARNS are the most critical infrastructures to invest in, especially the five locks identified as critical. Investing in these locks/dams improved the economic impact by fifty-three percent. However, investing in deepening the navigation channel or congested ports without investing in the critical locks/dams resulted in a limited economic impact improvement at seven percent and four percent respectively. Similarly, the economic impact of the Panama Canal expansion without investing in MKARNS infrastructure resulted in only a four percent economic improvement over the base scenario. Another significant result in this study is that investing altogether in channel deepening, congested ports, and critical locks/dams resulted in a higher economic impact improvement (ninety-two percent) than the summation of each individual investment scenarios. Finally, the economic impact of potential lock/dam disruptions is measured, and the results of the lack/dam scheduled unavailability disruption scenario resulted in economic losses of fifty percent of the base scenario, which translates into $1.1 billion in GDP annually. Moreover, the results of the unscheduled unavailabilities of lock/dam disruption scenario showed economic losses of twenty percent of that of the base scenario, which translates into 442 million in GDP every year.

To validate MarTranS boundary adequacy, structure assessment, dimensional consistency, parameter assessment, and extreme condition tests (Sterman, 2000) are conducted. The model was discussed throughout its development with two subject matter experts from public waterway transportation agencies. Moreover, related and current literature and governmental data sources helped assess the validity of the model parameters.

This study raised several research questions to be analyzed in the future. First, the generated tax during the study time frame could be re-invested in the inland waterway transportation system infrastructures to further improve the economic impact. Second, only lock/dam scheduled and unscheduled unavailability scenarios are studied in this paper, but other types of disruptions such as terrorist attacks, strikes and natural disasters could be considered to measure the corresponding economic impacts. Fourth, potential delays during the construction periods due to the investments in inland waterway transportation system infrastructure can be considered to account for the additional economic losses due to these delays. Third, a more detailed modeling effort of the alternate modes and the port operations can help strengthen MarTranS. Finally, MarTranS can be applied to different inland waterways to have a more holistic understanding of global inland waterway transportation systems.

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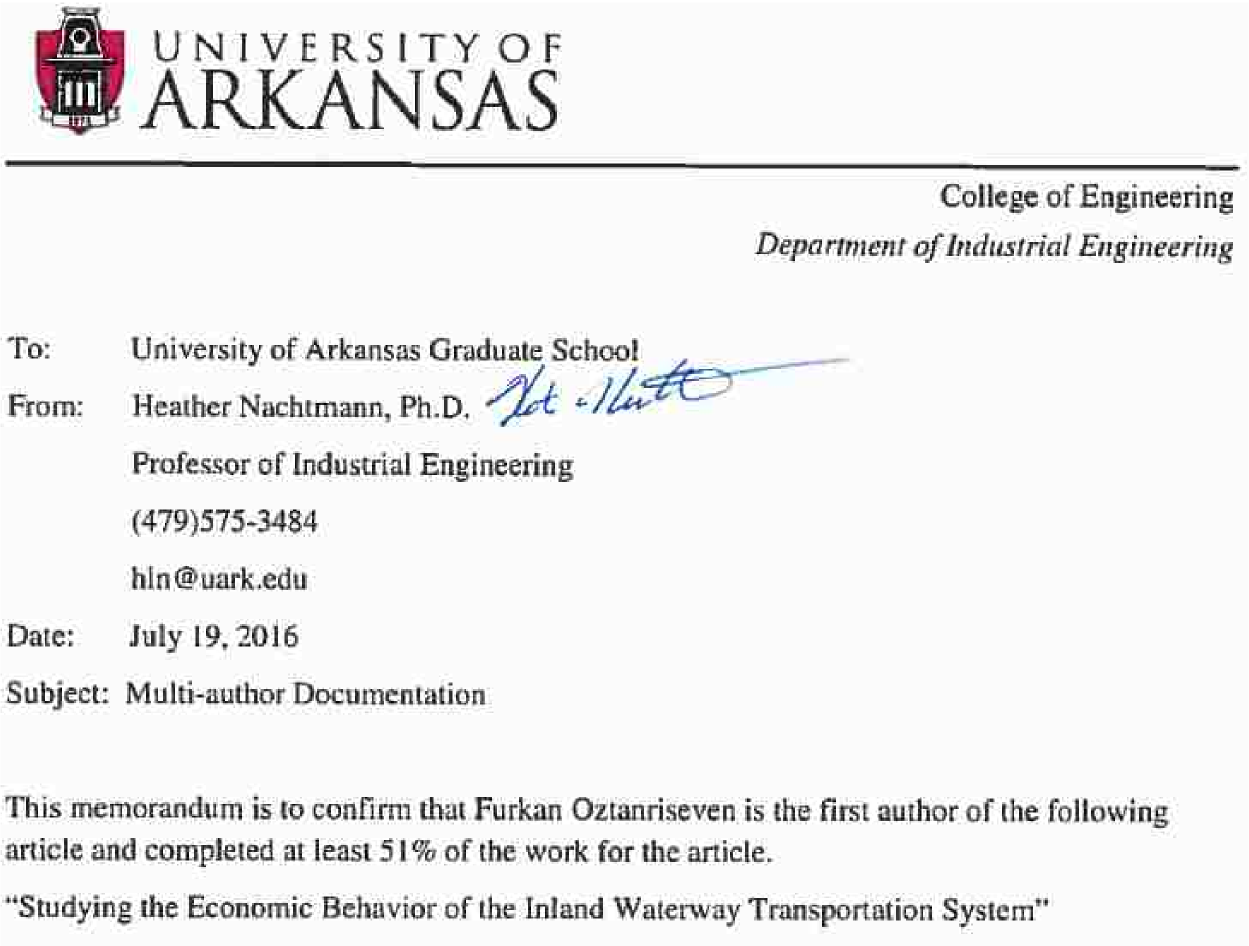
Disclaimer

Appendix 1



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This memorandum is to confirm that Furkan Oztanriseven is the first author of the following article and completed at least 51% of the work for the article.

"Studying the Economic Behavior of the Inland Waterway Transportation System"

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6. CONCLUSIONS AND FUTURE WORK

This chapter reviews the three main research contributions discussed in this dissertation, overviews the conclusions, and discusses future work. The main objective of this dissertation is to create decision support tools to assess the economic impacts of inland waterway transportation systems contingent upon real world scenarios including normal operation, disruption, infrastructure investment, and demand change to assist in making well-informed investment decisions. Decision support tools discussed in this dissertation can be employed by maritime transportation stakeholders such as the United States (U.S.) and State departments of transportation (DOTs), U.S. Army Corps of Engineers (USACE), U.S. Coast Guard (USCG), other maritime agencies, and private investors.

In chapter 2, a comprehensive literature review was conducted in the research area of economic analysis of the maritime transportation system. Our literature review reveals that there is a need for decision support tools to measure the economic impacts of the inland waterway transportation system operations and disruptions to enhance the associated economic impacts. Moreover, the conducted literature review provides a solid foundation for the developed methodologies in this dissertation. Our literature review concentrates on maritime transportation, economic analysis, input-output models, simulation studies, and disruptive events. Relevant literature is grouped into different classifications to better understand the current body of knowledge .The guidance and lessons learned from these earlier studies provides a sound starting point for developing our methodologies to measure the economic impacts of maritime transportation systems.

In the first research contribution (Chapter 3), the research objective aims to better understand the impacts of disruption duration, estimation, and commodity type on economic impact factors in the context of inland waterway transportation system. Forecasting economic impacts of inland waterway disruption decisions can empower system stakeholders to advance their preparedness and reduce economic losses. In this research, we contributed to the literature related to measuring the economic impacts of disruption decisions in the inland waterway transportation system. The simulation-based economic impact disruption decision model developed in Chapter 2 is generalizable to any inland waterway transportation system. The outcomes of the case study demonstrated that the expected duration of a disruption imposes whether decision makers are better off waiting for the waterway system to restore or diverting to an alternative mode of transportation. Moreover, estimation accuracy of disruption duration can aid the stakeholders to lessen the total cost induced by the disruptive event. The developed methodology is flexible for new advancements in the future, for instance capacity constraints for alternative modes of transportation and ports can be included. Since each element of inland waterway transportation system may be affected from a disruption differently, vulnerability of the system elements could be integrated to our model. Moreover, system resiliency could be considered to account for recovery period and recovery speed of each inland waterway transportation system component.

In the second research contribution (Chapter 4), a Maritime Transportation Simulator (MarTranS) is developed to model and better understand the relationships between inland waterway transportation system components and economic impact factors dynamically. MarTranS incorporates agent-based, discrete-event simulation, and system dynamics sub-models with multiregional input-output model and can improve investment decision making capabilities for maritime transportation stakeholders. By using publicly available data, MarTranS parameters can be altered and generalized to any inland waterway transportation system. To the best of our knowledge, this is the sole study that assesses the economic impacts of navigable inland waterways transportation system dynamically by using a multimethod simulation model. To demonstrate the applicability of MarTranS, we conduct a case study on the MKARNS. The case study illuminates that the economic impact of the MKARNS is not sustainable in the long-term without future investments in MKARNS infrastructure. Model results indicate that, in approximately two decades, the economic impact and commodity flow will decline to ten percent of their current values. Moreover, seventeen port docks and five locks/dams exceeded a utilization rate of eighty percent. These high utilization rates resulted in higher transportation delays and costs. Some of the possible future directions for this work are: 1) different kind of disruptions can be studied to measure their potential economic impacts, 2) to increase the economic impact, an optimization model can be integrated into MarTranS to identify the best simulation parameters, 3) the tax generated in the model can be considered for reinvestment into the system, and 4) alternative modes of transportation can be modeled in more detail to improve MarTranS.

In the third research contribution (Chapter 5), real world inland waterway transportation system scenario analyses are conducted utilizing MarTranS to measure the economic impacts of inland waterway transportation system. These scenarios are a base scenario, investment scenarios (deepening of navigation channel, port expansion, lock/dam rehabilitation, and system-wide investment), potential disruption scenarios (lock/dam scheduled and unscheduled unavailabilities), and the demand change scenario due to the effect of Panama Canal expansion. The MKARNS is also chosen as the study region to show an application of the developed MarTranS real world scenario analyses. The results illustrated that dry cargo and dry bulk commodities account for the highest economic impact at seventy-seven percent of the total.

Moreover, the locks/dams in the MKARNS are the most critical infrastructures and investing in these locks/dams improves economic impacts by fifty-three percent. However, investing solely in deepening the navigation channel or congested ports generated a limited increase in the economic impact at seven percent and four percent respectively. In addition, the economic impact of demand change due to the Panama Canal expansion scenario created only a four percent higher economic impact over the base scenario. Another significant finding of this study is that investing altogether in channel deepening, congested ports, and critical locks/dams created a higher economic impact (ninety-two percent over the base scenario) than the summation of each individual investment scenario. Finally, the economic impact of potential lock/dam disruptions is studied, and the lock/dam scheduled unavailability disruption scenario resulted in economic losses of fifty percent of the base scenario, which translates into $1.1 billion in GDP every year. Furthermore, the lock/dam unscheduled unavailability disruption scenario showed economic losses of twenty percent of that of the base scenario, which translates into $442 million in GDP every year. To the best of our knowledge, there is no research in relevant literature that studies potential economic impacts of inland waterway transportation system under real world scenarios including investment, disruption, and demand change by utilizing a multimethod simulation model. Understanding the relationships between the economic impacts of an inland waterway transportation system and corresponding real world scenarios can enhance the economic benefits and lead a competitive advantage over other transportation systems. Several research directions emerged as a result of this study. First, the generated tax during the study time frame can be re-invested in the inland waterway transportation system infrastructures to further improve the economic impact. Second, different types of disruptions can be studied with MarTranS, such as terrorist attacks, strikes and natural disasters. Third, a more detailed modeling effort of the alternate modes and the port operations, can enhance MarTranS. Finally, MarTranS can be applied to different inland waterways to have a more holistic understanding of global or the U.S. inland waterway transportation systems.