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Environmental hazard identification, assessment and control for a sustainable maritime transportation system

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ENVIRONMENTAL HAZARD IDENTIFICATION, ASSESSMENT AND CONTROL FOR A SUSTAINABLE MARITIME TRANSPORTATION SYSTEM

by

LIZZETTE PÉREZ LESPIER

A DISSERTATION

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This dissertation consists of the following articles that have been submitted for publication or are in the process of preparation for submission:

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Paper IV: Pages 95-116 will be submitted to the Journal of *Remote Sensing of the Environment*.

ABSTRACT

A demand exists to contribute towards the widening awareness of the need for sustainable maritime development and for coordinated maritime policies worldwide. Maritime shipping is considered the most eco-efficient mean of transportation and yet, is responsible for negative environmental impacts.

This dissertation focuses on developing data-driven decision support tools to evaluate the sustainable performance of MTS by focusing on the elements of the MTS that place stress on the environment. The first research contribution is a System Dynamics simulation model that examines the MTS resiliency after an extreme event and determines the sequence needed to restore the ocean-going port to its pre-event state. The second is a Decision-Making in Complex Environments (DMCE) tool developed by integrating fuzzy logic with a combination of Analytic Hierarchy Process (FAHP) and Techniques for Order Performance by Similarity to Ideal Solution (FTOPSIS) to quantify and rank preferred environmental impact indicators within MTS. The third is an extension to this DMCE tool by the integration of a Monte Carlo simulation in order to have a better understanding of the risks associated with the resulting rankings of those preferred environmental indicators. And, the fourth is a predictive model for the monitoring of vegetation changes near-port areas and to understand the long-term impacts that maritime activity has towards the environment. The developed models address the impacts MTS has on the natural environment and help achieve environmental sustainability of this complex system by evaluating the sustainability performance of the MTS.

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NOMENCLATURE

Symbol	Description
DMCE	Decision-Making in Complex Environments
FAHP	Fuzzy Analytical Hierarchy Process
FTOPSIS	Fuzzy Technique for Order Performance by Similarity to Ideal Solution
IMO	International Maritime Organization
KPI	Key Performance Indicators
MARPOL	Maritime Pollution
MC	Monte Carlo Simulation
MOO	Multi-Objective Optimization Model
MTS	Maritime Transportation System
NDVI	Normalized Difference Vegetation Index
PPB	Part per Billion
PPR	Port of Prince Rupert, British Columbia, Canada
TEU	Twenty-foot Equivalent Unit
TTVI	Thiam’s Transformed Vegetation Index

1. INTRODUCTION

This dissertation investigates one of the major disruptive problems encountered in Maritime Transportation Systems (MTS), the environmental sustainability. This dissertation looks at understanding how the system functions, remains competitive and achieves everything it needs without imposing huge harm towards the environment. Sustainable development is a challenging task that focuses on balancing that fine line between the competing needs to move forward technologically and economically, and the need to protect the environment. Moreover, it is also about examining the longer term effects of the system's actions and how it can be evaluated from an environmentally-sustainable standpoint and consequently how it may be improved. This dissertation focuses on developing data-driven decision support tools to evaluate the sustainable performance of MTS by focusing on the elements of the MTS that place stress on the environment. The data analytics tools and mathematical models 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, and environmental policy-makers in making well-informed decisions to determine the optimal paths to achieve sustainable development within the shipping sector.

1.1 RESEARCH MOTIVATION

The Maritime Transportation System (MTS) is vital to international trade and it is credited responsible of ninety percent of global trade by volume and over seventy percent by value (United Nations, 2016). It is considered the most cost-efficient and eco-friendly mode in comparison to the other major modes of transportation due to its ability to transport large quantities of freight over significant distances at lower costs (UNCTAD, 2016). Figure 1.1 shows a visual comparison of freight transport performance by mode, illustrating the strengths of the MTS when compared to the other major modes of transportation (Debyser , 2014).

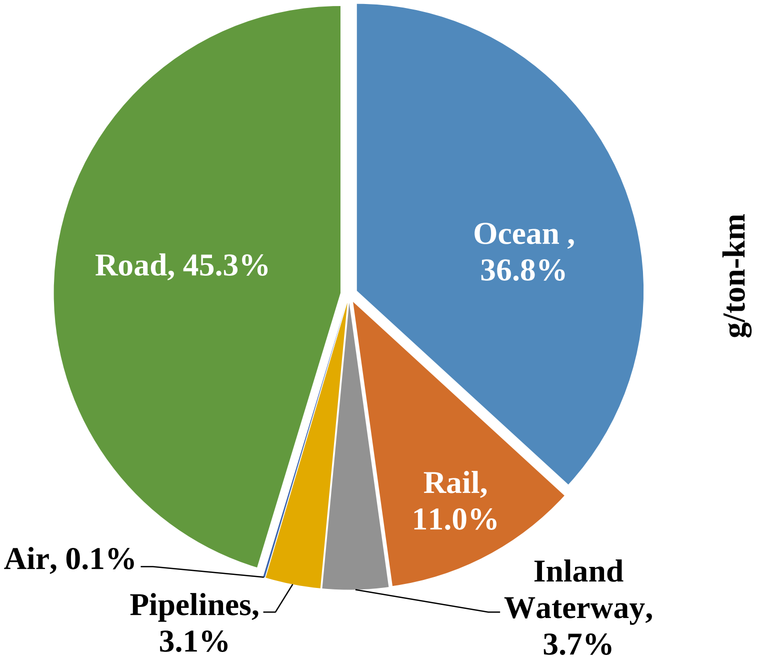
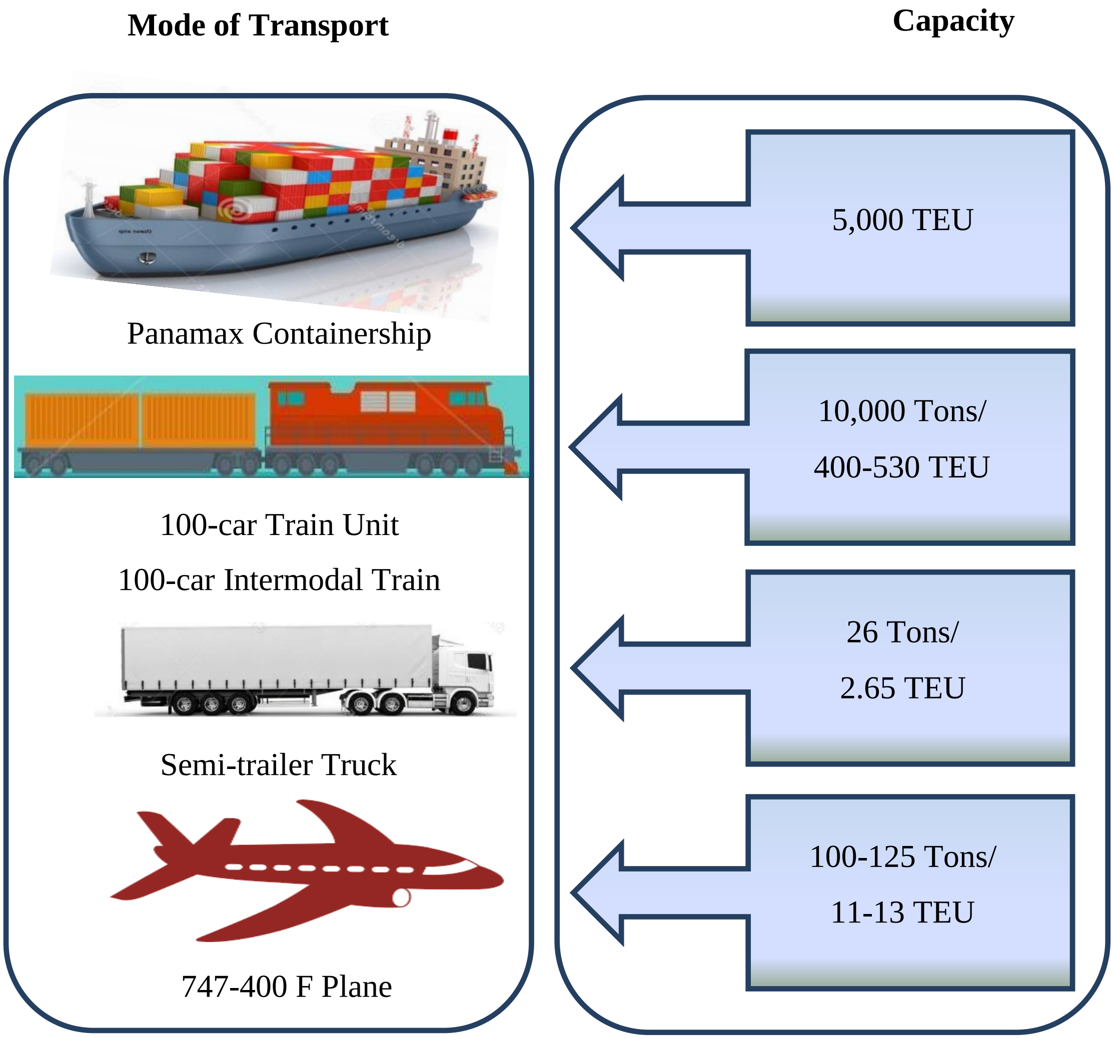


Figure 1.1. Freight Performance by Mode (ton-kilometers)

This relatively "invisible" service is an indispensable component of the world economy. MTS is considered the backbone of world trade and globalization, carrying goods and freight to all corners of the world. Hence, MTS is fundamental to sustaining economic growth and spreading prosperity throughout the world, fulfilling a critical social and economic function.

With international trade becoming a significant part of the world's economic activity, efficient freight transportation systems are becoming even more significant in supply chain's success. Maritime Transportation System is indispensable in a sustainable future global economy as it is the most environmentally sound mode of mass transport, both in energy efficiency and the prevention of pollution (IMO, 2012). For instance, in terms of cargo capacity, it is reported that one Panamax container can carry 5,000 Twenty-foot Equivalent Unit TEU, which is equivalent to the capacity of 13 100-car train units, 1,887 semi-trailer trucks, and 454 747-400F planes, as shown in Figure 1.2 (Rodrigue et al., 2017). Another advantage of MTS is that it is a cleaner choice of freight transport since shipping freight results in a more fuel efficient mode of transportation and with lower air emissions when compared to the other major modes of transportation (U.S. Environmental Protection Agency, 2017). Figure 1.3 illustrates a comparison of the CO_2 emissions by transportation mode (g/ton-km).



Note: Modes of transport not to scale.

Figure 1.2. Capacity Performance Comparison between Modes (Rodrigue et al., 2017)

Furthermore, when comparing transportation modes with regards to energy efficiency and using as comparison between the modes the number of miles one ton can carry per gallon of fuel, Maritime Transportation System is credited to have superior advantage over the other modes by carrying 576 miles-ton per gallon of fuel, whereas rail and truck carry 413 and 155 miles-ton per gallon of fuel, respectively (Tennessee-Tombigbee Waterway, 2017). Also, as Figure 1.4 shows, MTS is a cleaner choice of mean of transportation in that it has lower rate of spills of oil when compared to rail and truck (CORBA, 2017).

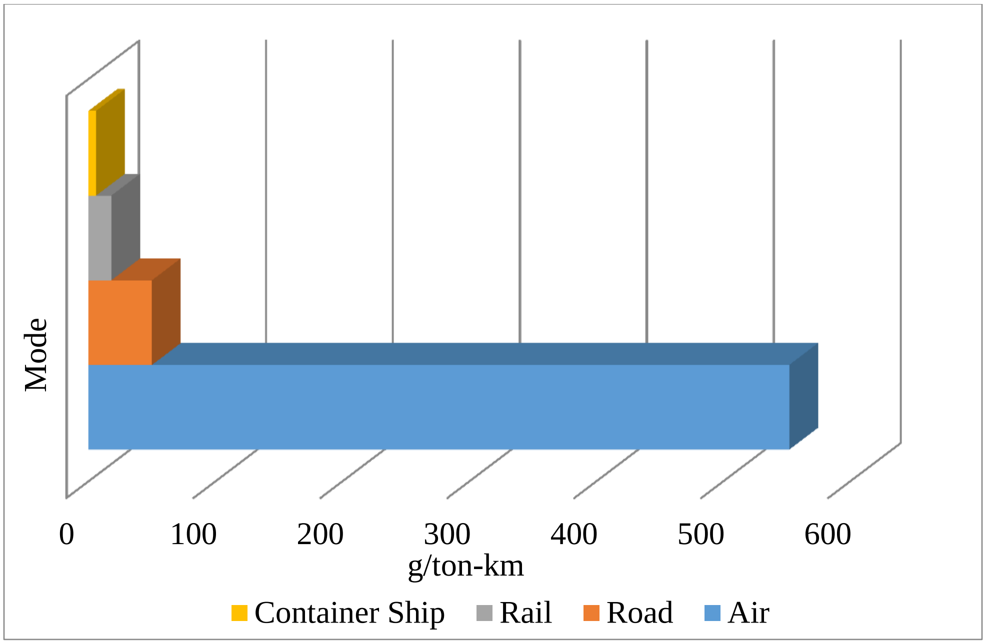


Figure1.3. CO_2 Emissions per Freight Transportation Mode (g/ton-km)

As international container traffic increases, ports will continue to increase in size and throughput. However, this growth should take place without imposing additional externalities that are harmful to the environment. Maritime Transportation System is an undeniable source of atmospheric emissions and its contribution to total global CO_2 emissions in 2012 was estimated at 2.3 % (IMO, 2012), and as the world economy becomes larger, emissions are expected to increase by 50 percent by year 2050 (Buhaug et al. 2009) (OECD & PBL Netherlands Environmental Assessment Agency, 2012).

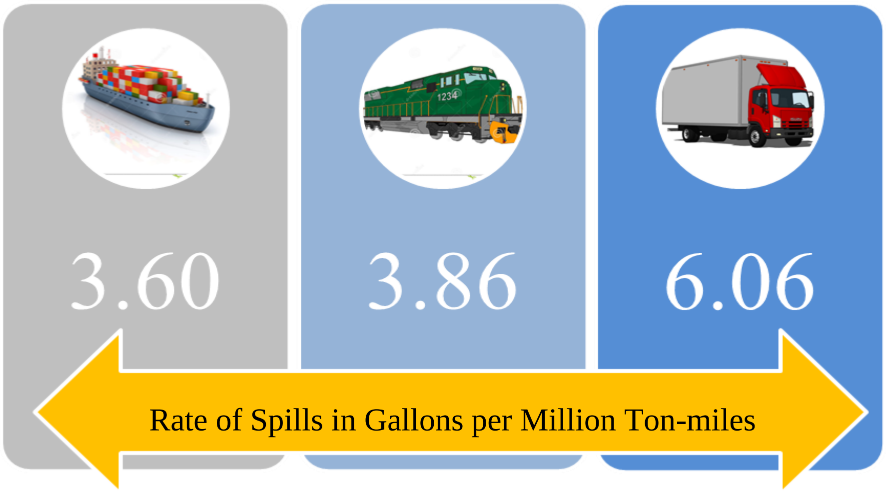


Figure1.4. Rate of Spills per g/ton-km per Transportation Mode

Moreover, studies have shown that the implementation of all available cost-efficient technologies aiming at reducing fuel consumption or at reducing emissions are insufficient for shipping to counteract the negative effects on the environment with the continued growth of the sector (Faber et al. 2011; Eide et al. 2011). Consequently, shipping companies face great pressure to fulfill their roles as socially responsible corporations while being cost competitive in a challenging global market (Lu et al., 2009).

Environmental sustainability has become an important subject among academics and the maritime industry in recent years (Chiu et al., 2014). Organizations in the shipping industry are abided with higher environmental awareness and they require their supply chain partners to attain eco-efficiency in their delivery services (Lee and Lam, 2012). However, many challenges exist to attain environmentally-sustainable practices by shipping companies such as relatively low level of project management development, lack of communication, and lack of knowledge and resources (Johnson et al, 2013). An extensive survey between ship owners and ship managers resulted in 72% of respondents agreeing that key performance indicators (KPI's) are necessary in shipping companies irrespective of the size and type of managed fleet (Konsta & Plomaritou, 2012). Moreover, only 22% agreed on actually utilizing key performance indicators in their daily shipping tasks (Konsta & Plomaritou, 2012). Studies have also found that out of all the performance problems found in the maritime industry, 8% are directly attributed to the lack of understanding of environmental issues (Konsta & Plomaritou, 2012).

A review of the literature on sustainability in the maritime industry focuses on how important it is to have a comprehensive understanding of the concept of sustainability in MTS. A port is considered to be sustainable if it finds an optimal balance between its performance as a business entity and its environmental performance (Broesterhuizen et al., 2014). Therefore, from the perspective of a shipping company, it is relevant to focus on what is preventing environmental efficiency improvements within the organization and what can be done to overcome existing barriers and hence improve their sustainable performance. There is a need to understand what customers (shippers) expect and require with regards to the environmental dimension in maritime activity, and determine how those desired requirements can be translated into their processes and operations. Hence it is essential for the MTS to adapt to twenty-first century concerns and implement best practices to reduce their environmental impacts at both, local and global levels.

This dissertation develops a decision-support tool with systematic metric and mathematical models for shipping companies to understand and improve their shipping activities based on environmental demands and ultimately attain environmental sustainability. This dissertation contributes to the widening awareness of the need for sustainable maritime development and for coordinated maritime policies worldwide, which in due course lead to a sustainable evolution of the MTS.

1.2 RESEARCH OBJECTIVES AND CONTRIBUTIONS

The overall goal of this research is to develop analytical tools and mathematical models for maritime stakeholders and managers to evaluate and understand the preferred green performance measures and determine the optimal paths to achieve sustainability, system effectiveness, efficiency, and describe the impacts of the maritime transportation system on the natural environment.

The research objectives and their respective contributions are broken down as follows:

Research 1: *Paper I* presented in this dissertation is published in the *Proceedings of the 2015 Industrial and Systems Engineering Research Conference (ISERC),* and its main objective was to perform a system analysis to identify the major elements in the shipping industry most likely to be impacted by the natural disaster of a hurricane. A System Dynamics simulation model was developed to show the applicability of the Systems Thinking approach when examining the detrimental effects an extreme event such as a hurricane has towards the elements composing the MTS. As result, sensitivity and what-if-analysis examined the effects on the system under study, the Port of San Juan, Puerto Rico under the disruptive impact of Hurricane Georges in 1998, and determined the sequence of steps and decisions needed to restore the system to its pre-event state.

Research 2: The research objective was to build a model for the evaluation of the preferred environmental impact indicators for a sustainable maritime transportation system. A Decision-Making in Complex Environments (DMCE) tool was developed by integrating fuzzy logic with a combination of Analytic Hierarchy Process (FAHP) and Techniques for Order Performance by Similarity to Ideal Solution (FTOPSIS) to quantify and rank preferred environmental impact indicators within a Maritime Transportation System. Such a model helps decision makers achieve environmental sustainability in complex systems. The model also provides environmental policy-makers in the shipping industry with an analytical tool that can evaluate tradeoffs within the system and identify possible alternatives to mitigate detrimental effects on the environment. Therefore, the combination of both methodologies with fuzzy logic is a superior tool for the understanding of the preferred criteria for sustainable MTS. This study has been submitted to *Transportation Research Part D: Transport and Environment* and presented in *Paper II* of this dissertation.

Research 3: In *Paper III,* we extended the DMCE tool developed in *Paper I.* A Monte Carlo Simulation was added to the DMCE tool that quantifies and ranks the preferred environmental impact indicators within a MTS, in order to complement the analysis of the DMCE tool to include a better understanding of the risks associated with the resulting rankings of those preferred environmental indicators. The Monte Carlo simulation enhances the tool by yielding the probabilities or risks associated with the ranking of each of the criteria and alternatives evaluated. This model assists decision-makers in the maritime industry with a better understanding of the tradeoffs within the rankings of the criteria and the alternatives preferred for a sustainable MTS.

Research 4: The objective of this research was to understand and explain the impact maritime activity has towards the environment near-port areas. The impact of MTS may be more significant at local and regional levels near port facilities. This work looks at one of the challenges of determining and being able to attribute the impact that maritime activity has towards vegetation near-port areas. In this work remote sensing using satellite images of the Port of Prince Rupert, British Columbia, Canada area were utilized to determine the environmental impact maritime activity has had over the vegetation near the port over the last 32 years. Data analytics was a vital component in the understanding of the long-term environmental impact that MTS has towards the environment. A multi-variate regression analysis was implemented to evaluate external variables or reasons, such as meteorological data, for the building of a model that explains the vegetation index behavior. This resulted in a time-series model for vegetation monitoring of near port areas. The developed models can help decision-makers evaluate the direct impact that maritime activity has towards the environment and help improve the performance of the system with regards to the environment. This research is presented in *Paper IV* of this dissertation.

Future Work: In this study, environmental performance indicators and policies will be used as criteria and decisive variables in order to develop a model that evaluates the sustainability performance of the MTS. Multi-Objective Optimization (MOO) is the methodology to be implemented for the optimization of conflicting objectives taking part in the maritime transportation system. This work is presented in the future work in *Section 2* of this dissertation.

1.3. METHODOLOGY AND STRUCTURE OF THE WORK

For this research work a certain set of procedures was followed to obtain the desired results of a model for the evaluation of the Maritime Transportation System with regards to environmental sustainability. Figure 1.5 includes a framework of the methodologies implemented and visually explains how these are connected to one another in order to attain the desired results of a model to evaluate the sustainable performance of the MTS.

The framework is designed on a bottom-up structure, where the first work performed in this research was the development of *Systems Thinking- System Dynamics Simulation* model in order to observe the disaster damage that a natural disaster such as a hurricane, has on different elements taking part in the MTS. This research is embodied below the yellow dashed-line in the framework. By understanding how the different components of the system behave when impacted by a large disaster's impact, once can determine their relationships and behavior and take the necessary steps to ameliorate performance and reduce the negative impact, thus maintaining a more effective flow of the system. The objective was to maintain that efficiency close to pre-event value hence, understanding the resiliency of the MTS under the distress of a natural disaster. After learning how to manage the disruptive impacts of a natural disaster on the port system found on Paper I, a better understanding of the physical relationship between the MTS and the environment is further studied.

The research followed with the Decision-making in Complex Environments (DMCE) tool by integrating fuzzy logic with a combination of Analytic Hierarchy Process (FAHP) and Techniques for Order Performance by Similarity to Ideal Solution (FTOPSIS) in order to understand those preferred environmental impact indicators within a Maritime Transportation System; found in Paper II. This would help have a better understanding of the local impact maritime activity has towards the environment. As an extension to this model, a Monte Carlo simulation was added to the DMCE tool on order to understand the risk associated with selection of criteria and alternatives, presented in detail in Paper III.

Succeeding, at the bottom right above the yellow dashed line of the framework, the gathering of satellite images to use remote sensing took place in order to understand the broader impact maritime activity has towards the vegetation near the port. As observed in the framework, the methodology of Thiam's Transformed Vegetation Index (TTVI) was utilized to extract data on the vegetation changes throughout the years. This recollected data was then utilized to perform a time series analysis, which ultimately was added to external variables to construct a multi-variate regression model for the understanding of the long-term impact that maritime activity has towards the environment. This work can be found in Paper IV.

Lastly, all this work will lead to the building of a multi-objective optimization (MOO) model for the performance evaluation of the Maritime Transportation System as an environmentally-sustainable system, found in *Future Work* of *Section 2*.

Detailed description on how the development of the different methods and models presented in this dissertation took place can be found on their respective papers and section included in this dissertation.

1.4. ORGANIZATION OF DISSERTATION

Section 1 introduces the Maritime Transportation System (MTS) and presents the research motivation and research objectives and contributions of this dissertation.

Follows the dissemination of the papers included as part of this dissertation. Paper I presents a paper published in *Proceedings of the 2015 Industrial and Systems Engineering Research Conference (ISERC),* entitled "A Systems Thinking Approach to Post-Disaster Restoration of Maritime Transportation Systems" (Pérez Lespier et al., 2015). Paper II presents a manuscript submitted to the international journal *Transportation Research Part D: Transport and Environment*, entitled "A Model for the Evaluation of Environmental Impact Indicators for a Sustainable Maritime Transportation System" (Pérez Lespier et al., 2017). An extension to the Decision-Making in Complex Environments (DMCE) tool developed in Paper II, which consists in adding a Monte Carlo simulation to the tool, is presented in Paper III. Paper IV develops the mathematical models that explain the direct impact maritime activity has towards the vegetation near the port.

Lastly, the overall conclusions and future work of this dissertation are disseminated in Section 2. In Future Work, a multi-objective optimization model is being developed to evaluate the sustainability performance of the maritime transportation system given the conflicting objective of maximizing the system’s efficiency and the minimizing of its environmental impacts is discussed.

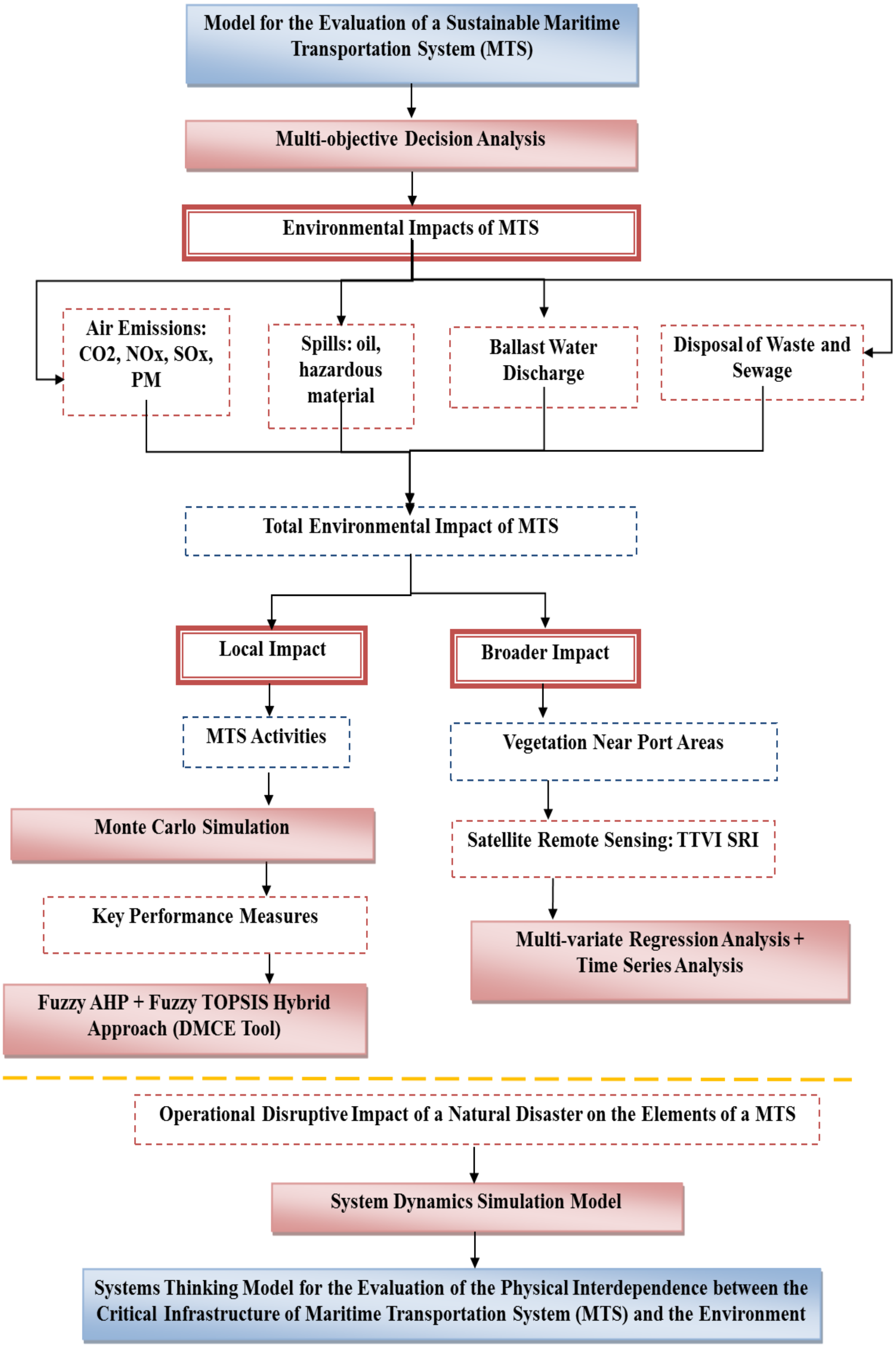


Figure 1.5. Methodology Framework

PAPER

I. A SYSTEMS THINKING APPROACH TO POST-DISASTER RESTORATION OF MARITIME TRANSPORTATION SYSTEMS

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ABSTRACT

A *Systems Thinking* approach is used to examine elements of a maritime transportation system that are most likely to be impacted by an extreme event. The majority of the literature uses a high-level view that can fail to capture the damage at the sub-system elements. This work uses a system dynamics simulation for a better view and understanding of the Port of San Juan, Puerto Rico, as a whole system and uses Hurricane Georges (1998), as a representative disruptive event. The model focuses on the impacts of natural disasters at the sub-system level with a final goal of determining the sequence needed to restore an ocean-going port to its pre-event state. This work in progress details model development and outlines steps for using real-world information to assist maritime port manager planning and recommendations for best practices to mitigate disaster damage.

KEYWORDS

Systems thinking, maritime transportation, disaster restoration, port elements, disaster resilience

1. INTRODUCTION

1.1 MARITIME TRANSPORTATION SYSTEM

Maritime Transportation Systems (MTS) are an important component of transportation systems at a global and national level. Approximately 80% of world trade goods are transported on ships [1]. Maritime Transportation Systems are exposed to a variety of organizational and environmental risks that may disrupt their services and potentially result in large amounts of losses, either direct or indirect. In this paper, ‘system’ refers to a group of connected elements that form the complex MTS. In the wake of a disaster, serious damage to transportation infrastructure can have a far-reaching impact on the ability of the affected systems to return to pre-event capacity. These adverse impacts can affect not only the primary system’s functions and operations, but also any connecting system that relies on the functionality of primary system; because the damage to connectivity is difficult to predict, this response uncertainty increases. Mansouri et al. categorize the causes of uncertainty into four major groups: natural, organizational, technological, and human factors [2]. Since disruption as a result of an extreme event is inevitable, it is critical that systems be understood from both a design and an operational perspective so that planners can adopt appropriate resilience strategies as part of the restoration process.

This work focuses on creating an MTS representation and understanding the sources of uncertainty resulting from a large disaster such as a hurricane. A model is built to calculate the impact of disaster damage on unloading time and freight capacity for an affected port. This model, then, enables the estimation of how long it takes for the system to recover from such disaster.

2. MOTIVATION OF RESEARCH

2.1 PORT OF SAN JUAN

Puerto Rico is the largest and most populous island area of the United States. As such, it depends heavily on maritime transportation to move goods to and from the island [3]. Puerto Rico has experienced a number of large disasters. After each disaster, there is significant focus on the efforts to recover and restore the effected systems to their intended behavior, as well as the built environment’s ability to withstand devastating weather events. The Port of San Juan, PR, has suffered damage from past hurricane disasters that severely impacted its operations. The Port of San Juan is the main port for importing and exporting goods for Puerto Rico, and is also of extreme importance for nearby regions. This study constitutes an essential first step in understanding the behavior of the transportation elements for island systems, as applied to the Port of San Juan, in order to aid in a strategic recovery in the aftermath of a large-scale disruption.

The Port of San Juan’s cargo facilities are located on the southern portion of San Juan Bay, known as Puerto Nuevo Harbor district shown in Figure 1. Of the approximately eight cargo terminals, five are located in the Puerto Nuevo district of San Juan. This project focuses on containerized maritime shipments, and therefore the Puerto Nuevo Harbor of the Port of San Juan is emphasized in the model. The location of the Puerto Nuevo Harbor port's cargo facilities give it instant access to Puerto Rico's expressway system and several major local routes, which allows for the fast and efficient transportation of goods throughout the San Juan metropolitan area and the rest of the island. Hence, Puerto Nuevo Harbor port is of upmost importance for efficiency in island operations and functions.

Figure 1. Map of San Juan Bay [4]

Puerto Rico’s major trading partner is domestic (United States) as shown in Table 1. This relationship is used to create a model based upon the availability of importation data to the Port of San Juan, PR, from the rest of the United States.

Table 1.Puerto Rico’s Main Trading Partners Fiscal Year 2013 (FY2013) [5]

Country	**Exports***	**Imports***
Australia	226,509.90	22,672.40
Austria	977,586.50	7,932.50
Belgium	2,657,959.30	239,372.00
Brazil	233,053.00	1,198,906.70
China	602,191.50	855,023.50
Dominican Republic	482,475.50	514,728.20
France	1,023,648.60	264,102.70
Germany	521,736.10	416,795.40
Ireland	101,194.60	6,792,443.60
Italy	1,728,740.50	433,596.70
Japan	1,495,949.80	1,875,954.00
Mexico	363,873.50	466,610.40
Netherlands	1,877,226.40	645,531.90
Singapore	193,982.50	3,961,604.40
Spain	1,455,741.80	339,291.00
United Kingdom	1,528,171.00	639,598.40
United States	44,665,838.10	20,454,933.60
Other Countries	2,260,990.40	6,009,606.20
Total	62,396,869.00	45,038,703.80

*In thousands of dollars

2.2 HURRICANE GEORGES

Hurricane Georges formed on September 15, 1998, as a tropical depression 300 miles south-southwest of the Cape Verde Islands in the far eastern Atlantic. Georges strengthened to a hurricane on September 17th and reached Category 4 intensity on September 19th. Georges tracked across Puerto Rico the evening of the 21st as shown in Figure 2. The track over the mountainous terrain weakened Georges to a Category 1 hurricane. However, Georges began to intensify once again as it moved north of the Cuban coast and tracked west-northwest toward the Gulf of Mexico [6]. Figure 2 depicts Hurricane Georges track through the U.S. Virgin Islands and Puerto Rico. Each circle represents the hurricane's position, and each is labeled with date and time (Atlantic Standard Time), maximum sustained winds and minimum central pressure in millibars (mb) provided [7].

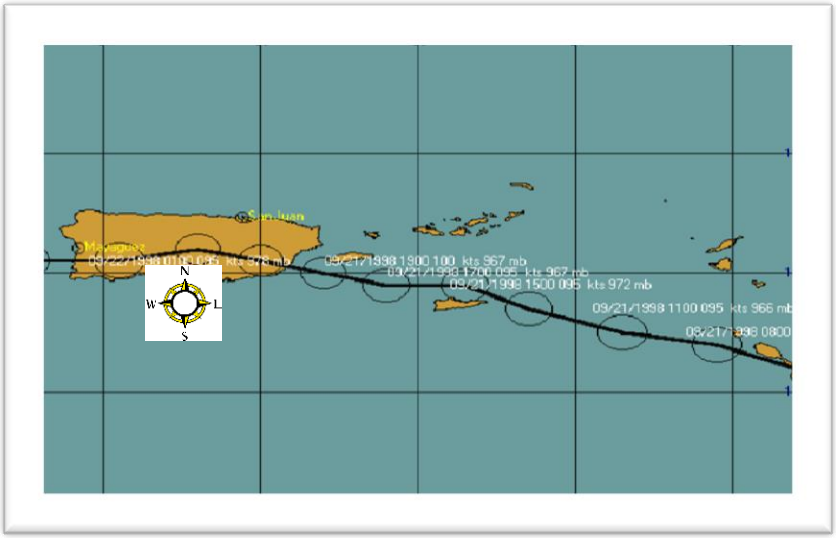


Figure 2. Hurricane Georges' path through U.S. Virgin Islands and Puerto Rico[7]

The Doppler weather radar information given in Figure 3 was taken at 17:26 on September 21, 1998, and shows the island of Vieques (off the southeast coast of Puerto Rico) inside the eye of Hurricane Georges. Colors in the scale at the upper right of the figure indicate the intensity of the storm; purple and red represent the highest intensity thunderstorms, followed by yellow, green and then blue in descending intensity [8]. Ground reports following the event detail extensive damage to the Port of San Juan in terms of its facilities and resulting in significant loss of product flows and revenues for Puerto Rico [6].

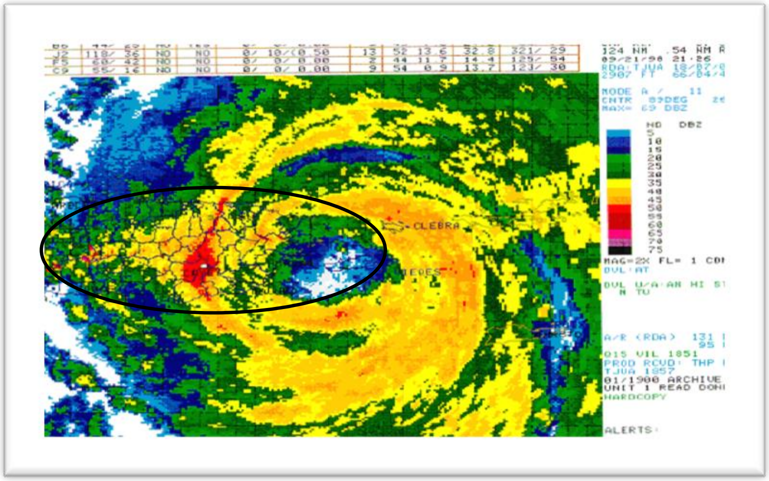


Figure 3. Doppler weather radar observation of Hurricane Georges over Puerto Rico, September 21, 1998 [8]

3. LITERATURE REVIEW

Disasters have always been a subject of interest, but in the last decade research has increased due to a succession of unpredicted events such as Hurricane Katrina, the Indian Ocean tsunami, and the Deepwater Horizon oil spill in the Gulf of Mexico. The proper handling of disaster situations is vital to minimizing their impacts and restoring functions to pre-event states. To date, research has helped in identifying the importance of early warning systems and strategies for recoveries [9].

The bulk of the literature considers either emergency response or short-term recovery strategies. In addition, many studies do not consider the interdependence between critical infrastructure systems. To properly understand disaster recovery, a complex adaptive systems approach is used in order to capture emergent behaviors [10-12] and evaluate post-disaster resilience.

3.1 RESIELIENCE DEFINITION

When a disruption occurs in the MTS, various economic, social, political forces call for the system to recover efficiently to its pre-disruption stage. The efficiency of this restoration process is a metric of the resiliency of a system. For this paper, resiliency is defined as the time required to return the MTS to 80% of its pre-disaster capability. The term ‘resiliency’ was proposed by Holling [13] for the first time in the context of ecological research to distinguish between the system (ecosystem or society) that persists in a “state of equilibrium” or stability; and how dynamic systems behave in response to stress as they move to instability from equilibrium. Resiliency in a System of Systems (SoS) such as MTS, can be defined as a function of system vulnerability against a potential disruption, and its adaptive capacity in recovering to an acceptable level of service within a reasonable timeframe after being affected. Overall, the literature shows that resiliency has two dimensions: vulnerability and adaptive capacity [14]. Research on resiliency in MTS has helped in the understanding of this complex system. Omer et al. [15] and Croope and McNeil [16] used a Systems Dynamics (SD) approach to study the resiliency of the MTS. Conclusions from both studies are similar in suggesting that the construction of a resilient MTS can minimize potential losses. But in order to construct a resilient system, it is important to first understand the system’s weaknesses at the time of a disruption or natural disaster. Research shows that maritime ports are particularly vulnerable to disaster-related disruptions due to their geographic locations, and such disruptions will result in negative local and global economic impacts. To decrease vulnerability and increase resiliency, security policies are established by governments and private entities. Yeo, Pak, and Yang [17] 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 [17].

3.2 SYSTEM DYNAMICS

System Dynamics (SD) is “a methodology for studying and managing complex feedback systems” [18]. Jay Forrester describes SD as 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” [18]. 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 and helps in the visualization of behaviors under different circumstances.

A review of the literature has demonstrated that System Dynamics is a viable methodology to model disruption complexities and uncertainties when it comes to analyzing and understanding complex systems such as the MTS [19].

4. METHODOLOGY

4.1 SYSTEMS THINKING

Systems thinking is a holistic approach for analysis that focuses on the way that a system's constituent parts interrelate and how systems work over time. This approach has its foundation in the field of System Dynamics founded by Forrester [20]. While traditional models of system architecture break down and analyze each system component separately, a systems thinking approach investigates the interconnectivity of all components, both within the given system and throughout other systems, necessary for proper functionality. The appeal of using a systems thinking approach is that it is extremely effective for solving the most difficult types of problems, namely complex systems [20]. A MTS is such a complex system. A systems thinking approach is then applied to the MTS associated with the port at San Juan, Puerto Rico, to model the formation of relationships between system elements and their interaction with the environment. Subsequent modelling will map how the interconnectivity between the system elements give rise to the collective behaviors of the entire system and how these behaviors break down in the aftermath of a disaster. The end result will be the parameterization of the resiliency for the port of San Juan MTS.

Taking this complex, highly dynamic, and uncertain state of interrelations into account, a MTS must be resilient. In other words, it must be capable of maintaining a certain level of operation in the face of disruptions. Therefore, it is necessary for the system to plan proactively and prepare for effective and quick responses. 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.

Mansouri et al. applied multiple systemic tools such as *Systemigrams* to study critical properties of the MTS, such as resilience and security, to more effectively understand the systemic interrelationships in an MTS [21]. Other studies [22 - 24] have used systems thinking and its fuzzy logic approach to understand and evaluate the complexities to which maritime systems are always exposed due to a variety of organizational and environmental risks that may disrupt their services and potentially result in more complicated processes. The security issue is an example of a MTS complicated process. Even when considered as a single factor in MTS, it is almost impossible to take every contingency into account [22 - 24].

5. MODEL

Most complex systems have one or more metrics that measure system performance. In MTS, disruption not only limits the capability of the port to send and receive goods, but also increases the time to transport goods from source to destination. Thus, the questions are: what is the port’s ability to receive the goods and how long will it take to transport such goods? These two metrics can be identified as: tonnage resiliency and time resiliency. The tonnage resiliency reflects the ability of the system to reliably send and receive the goods. The time resiliency represents the impact of the natural disaster disruptions on the time required to send and receive the goods. Although these two metrics are introduced here, analyses of these metrics are beyond the scope of this paper. The resiliency of the system, therefore, is parameterized based only on how the system efficiency (throughput of tonnage over time) is impacted by a disaster and how long it takes to return the system to 80% of its pre-event operational capabilities.

5.1 MODEL VARIABLES

In System Dynamics modeling variables are grouped into endogenous, exogenous, and excluded variables [18] as shown in Table 2. In SD modeling, the researcher develops a hypothesis that can explain the phenomena endogenously. The exogenous variables in a SD model are not part of the feedback structure, but they do impact the system behavior. The third group of existing variables is the excluded variables, but excluded variables are not considered in the model. Table 2 shows the variables that take part in the model and their respective groups. Table 3 shows the capacity of ships and freight handled by the port of San Juan in 1998.

Table 2. Model Variables and Identification of Group

Variable	**Group**
Vessels at USA destined for San Juan	Endogenous
Vessels waiting to be processed at San Juan	Endogenous
Vessels stuck at United States	Endogenous
San Juan Arrival Rate	Exogenous
San Juan Processing Rate	Exogenous
Max number of vessels allowed at San Juan	Exogenous
Vessels processed in San Juan	Exogenous
San Juan Port Capacity	Endogenous
Natural Disaster Impact	Exogenous
Time waiting at San Juan	Endogenous
Travel time from United States to San Juan	Exogenous
Total System Travel Time	Endogenous
Technological Disruptions	Excluded
Organizational Disruptions	Excluded
Human Factor Disruptions	Excluded

Table 3. Tonnage and Number of Vessels moving through the Port of San Juan in the Calendar Year, 1998 [4]

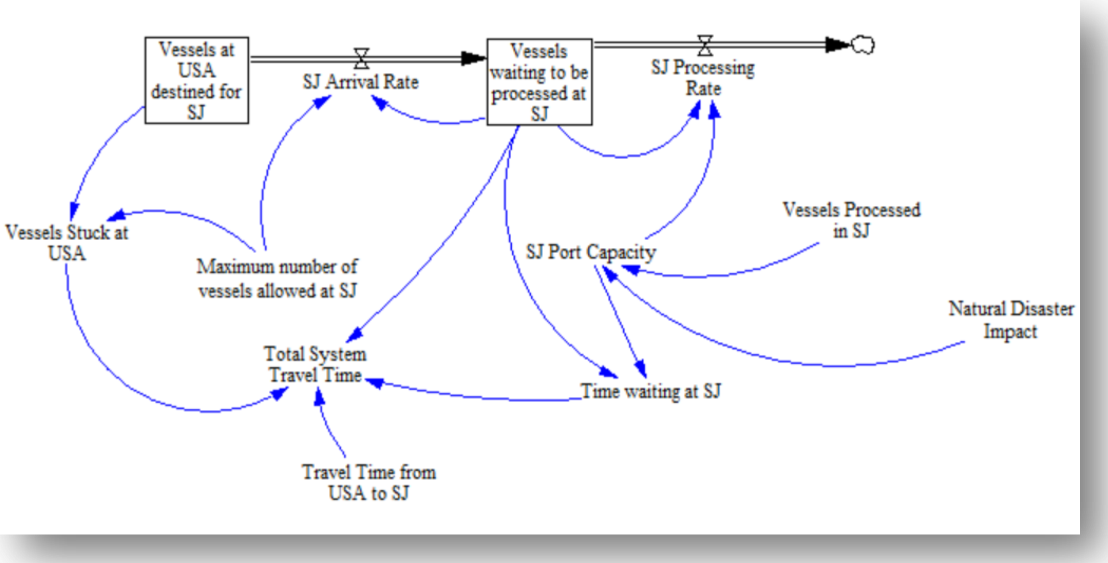
	Monthly		**Daily**	
Month	**Vessels**	**Tonnage**	**Vessels**	**Tonnage**
January	376	8,262,321	12.1	266,526
February	338	7,781,015	12.1	277,893
March	415	8,649,894	13.4	279,029
April	361	8,114,878	12.0	270,496
May	312	5,397,654	10.1	174,118
June	300	4,435,518	10.0	147,850
July	318	5,686,001	10.3	183,420
August	313	5,947,542	10.4	198,250
September	267	5,119,825	8.9	170,660
October	281	6,267,370	9.8	202,173
November	213	8,622,053	7.1	287,400
December	305	8,344,403	9.8	269,175
Year Total	**3,799**	**82,628,474**		
Daily Average Minimum			**7.1**	**147,850**
Daily Average Maximum			**13.4**	**287,400**
Daily Average			**10.4**	**227,250**

5.2 STOCK AND FLOW MODEL

Figure 4 presents the SD stock and flow model developed to characterize the system and study its behavior under a disruptive event.

5.3 MODEL EQUATIONS AND FORMULATION

The model is designed using the theory of network optimization, where the objective function is to minimize the total time of operation in the system. The optimization problem maximizes the tonnage flow between the ports of the United States (USA) and San Juan (SJ) in a given amount of time. This is shown in Figure 4. The model was calibrated using simulated data to evaluate the impacts of disasters on congestion as determined by unloading time and capacity interruptions.



*SJ refers to the port of San Juan, Puerto Rico, and USA to the United States of America

Figure 4. SD Model for measuring how long (in days) it takes for the system to recover from a disruptive event

The approximation of total tonnage per day is based on information on total cargo volume provided by the Ports Authority of Puerto Rico. The shipping times are estimated from historical data. As indicated by the stock and flow model shown in Figure 4, a decrease in the port capacity due to the impact of the disaster will increase the total time it takes to process the vessels.

The SD model is made up of two stocks. The first stock is the *Vessels at USA destined to San Juan,* and this stock includes the total amount of vessels that travel daily from the USA to the Port of SJ. The formulation for calculating *Vessels at USA destined to San Juan* is shown in equation 1*:*

$$\begin{gathered} Vessels\ at\ USA\ destined\ to\ SJ = \\ Initial\ amount\ of\ vessels - SJ\ arrival\ rate \end{gathered} \tag{1}$$

An assumption of the SD model is that the Port of SJ is able to process a certain number of vessels per day, which is specified by the *Vessels Processed in SJ* parameter. When and if this parameter is exceeded, no more vessels are processed to the Port of SJ, which consequently will increase the *Vessels Stuck at USA* parameter. If the maximum number of vessels per day entering the port of San Juan is not exceeded, the usual amount of vessels should be processed from USA at Port of SJ. Therefore, the *Vessels Stuck at USA* parameter is defined by the If-logic in equation (2).

$$\begin{aligned}&IF\ (Vessels\ at\ USA\ destined\ to\ SJ > Max\ num\ of\ vessels\ allowed\ at\ SJ)\ THEN,\\&\qquad Vessels\ stuck\ at\ USA =\\&Vessels\ at\ USA\ destined\ to\ SJ - Max\ num\ of\ vessesls\ allowed\ at\ SJ\\&ELSE,\\&\qquad Vessels\ stuck\ at\ USA = 0\end{aligned} \tag{2}$$

And the *SJ Arrival Rate* would be defined by the If-logic shown in equation (3).

$$\begin{aligned}&IF\ (Vessels\ waiting\ to\ be\ processed\ at\ SJ\\&\qquad > Max\ num\ of\ vessels\ allowed\ at\ SJ)\ THEN,\\&\qquad\qquad SJ\ Arrival\ Rate = 0\\&\qquad ELSE,\\&\qquad\qquad SJ\ Arrival\ Rate\\&= Max\ num\ of\ vessels\ allowed\ at\ SJ\\&- Vessels\ waiting\ to\ be\ processed\ at\ SJ\end{aligned} \tag{3}$$

Then, the second stock in the SD model is *Vessels waiting to be processed at SJ*, and is calculated by equation (4).

$$\begin{aligned}&Vessels\ waiting\ to\ be\ processed\ at\ SJ =\\&SJ\ Arrival\ Rate - SJ\ Processing\ Rate\end{aligned} \tag{4}$$

The processing rate for the Port of SJ is affected by the *SJ Port Capacity* measured in tonnage per day. This capacity decreases in proportion to the damage inflicted by a disaster on the port facilities. The *natural disaster impact factor* follows a random distribution from 0.1 to 0.8, in order to represent the different categories of the hurricane affecting the system. This *natural disaster impact factor* has a direct impact towards the capacity of the Port of SJ. Therefore, one will notice in the results that normally the port processes the vessels as they arrive, but under the disruption caused by large disasters, such as a hurricane, a reduction in the capacity of the Port of SJ will occur, causing the processing rate to be reduced as well, and consequently affecting the total response time of the system.

An assumption made in the SD model is that the Port of SJ starts by operating at maximum capacity, meaning that it is able to process a specified number of vessels per day. Then, the parameter of *Time waiting at SJ* is calculated by dividing the number of vessels that are waiting to be processed by the Port of SJ's capacity, using the If-logic statement shown in equation (5),

$$\begin{array}{l} IF\ (Vessels\ waiting\ to\ be\ processed\ at\ SJ > \ SJ\ Port\ Capacity)\ THEN, \\ \qquad Time\ waiting\ at\ SJ = 1 \\ \quad ELSE, \\ \qquad Time\ waiting\ at\ SJ = \\ Vessels\ waiting\ to\ be\ processed\ at\ SJ \Big/ _{SJ\ Port\ Capacity} \end{array} \tag{5}$$

The final output of the SD model is the *Total System Travel Time*, which calculates the overall system travel time for the duration of the disruption or natural disaster. This parameter indicates the number of days require to restore the system to 80% of its full operational capacity; this *Total System Travel Time* is calculated with equation (6).

$$\begin{gathered} Total\ System\ Travel\ Time = \\ Travel\ Time\ from\ USA\ to\ SJ + Time\ Waiting\ at\ SJ * \\ (Vessels\ waiting\ to\ be\ processed\ at\ SJ + Vessels\ stuck\ at\ USA) \end{gathered} \tag{6}$$

6. PRELIMINARY DISCUSSION AND CONCLUSION

This paper outlines how systems thinking can guide the development of a systems dynamics model for port management. A systems thinking approach is used to study the Port of San Juan under the disruptive impact of a representative natural disaster such as Hurricane Georges (1998). The model can be used to simulate the incoming freight from the USA to the Port of San Juan, Puerto Rico, in order to determine how the Port of San Juan's capacity might be affected by hurricane-style disasters. The total time required for the port system to operate and process the amount of vessels normally versus under disruption is compared as part of the simulation framework to determine system resilience. For the purposes of the analysis in the model, the quantity of vessels that need to be unloaded is determined, meaning that the scheduling of the vessels is not altered. The data used in the model were the average tonnage presented in Table 3 transformed from a monthly unit to a daily unit. A daily unit is preferred for a more realistic depiction of the impact factors because this tends to match the duration of large disasters.

With this model one can observe that the disaster damage will have an impact on different elements taking part in the MTS. For example, the processing rate at the Port of SJ shown in Figure 5 will be adversely affected by the disaster damage (processing rate drops to 125,000 tons/day immediately after the disaster, climbing back to almost 4 tons/day after 5 days of restoration). This is also be true for the ability of the port of San Juan to turn around vessels (Figure 6), The capacity of the port to load and unload vessels (Figure 7) and also the travel time for the vessels to sail from the USA to SJ (since they will time their arrival to their ability to enter the port), which is shown in Figure 8. This total time helps in the understanding of the resiliency of the MTS, in order to determine the time required for the system to return to its normal operating state. As observed in

Figure 6, it takes the Port of SJ an average of 5 days to return to its pre-event operating capacity. According to interviews with subject-matter experts and personnel at the Ports Authority of San Juan, PR, it took approximately 1 week to return to normal operations, excluding the reconstruction of infrastructural damage in the aftermath of Hurricane Georges. The model, therefore, has shown a gratifying agreement between resiliency predictions and the resiliency time associated with damage caused by Hurricane Georges.

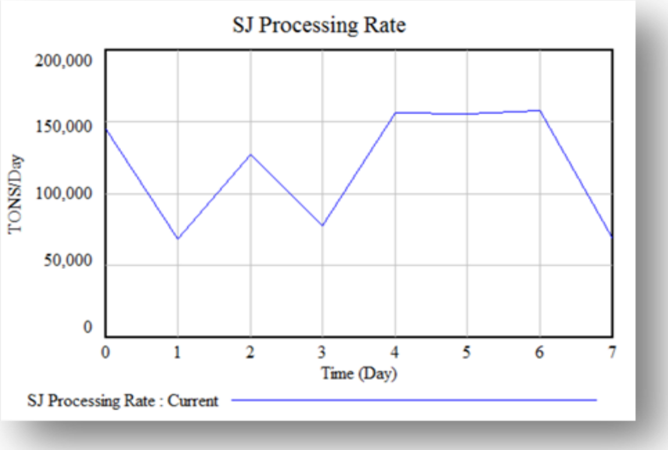


Figure 5. SJ Processing Rate Graph

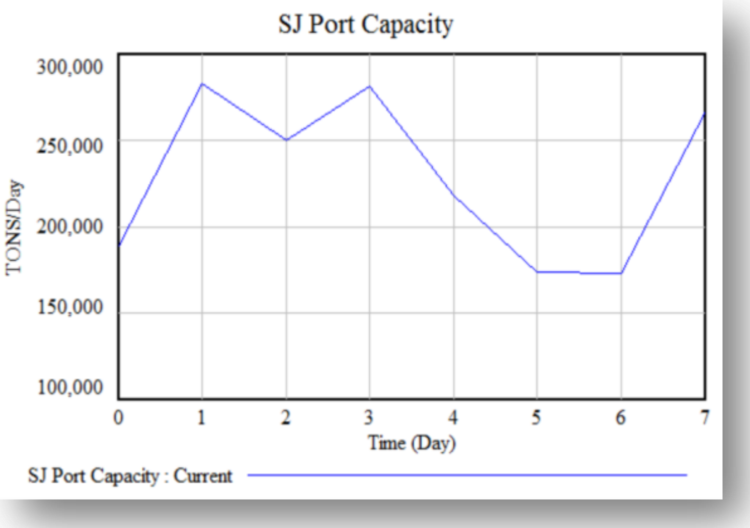


Figure 6. SJ Port Capacity Graph

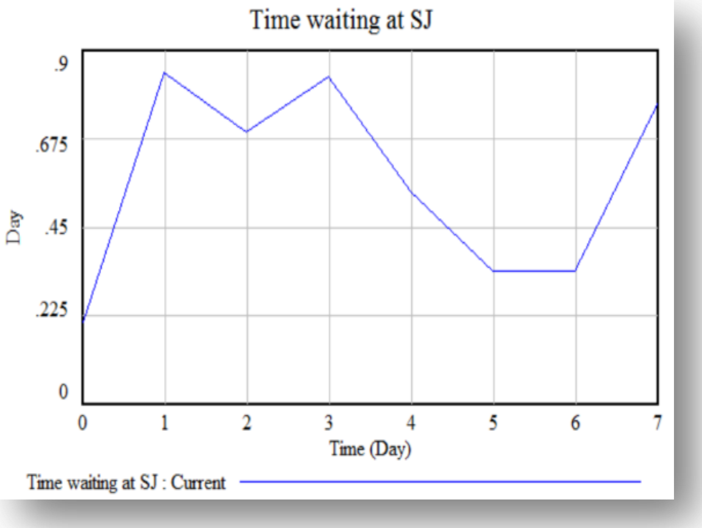


Figure 7. Time Waiting at SJ Graph

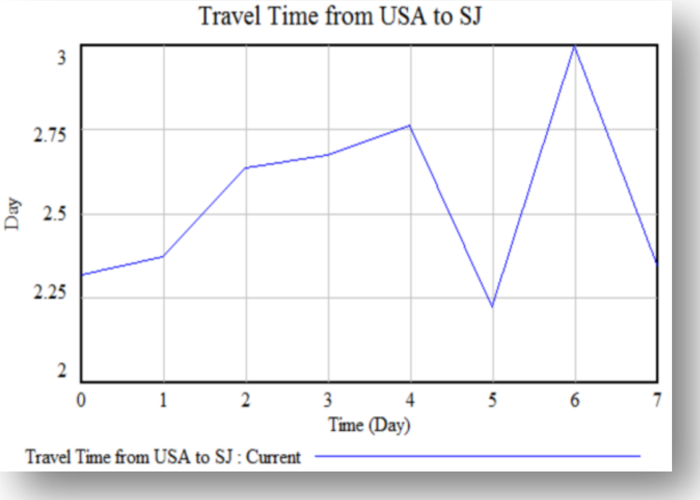


Figure 8. Travel Time from USA to SJ Graph

By understanding how the different components of the system behave when impacted by a large disaster's impact factor, one can determine their relationships and behavior and take the necessary steps to ameliorate performance and reduce the negative impact, thus maintaining a more effective flow in the system. Because efficiency is a measurement of the amount of throughput (tonnage) over a period of time (day), the objective is to maintain that efficiency close to the pre-event value. Some elements of the model were chosen to be held fixed during these analyses; these elements included travel time from USA to SJ and freight capacity. The elements that were allowed to vary, such as the processing time, are considered the most critically important when determining a mitigation plan for the restoration of the system to its pre-event operational capability. The model aids in understanding how a disasters impact the different elements of MTS, and therefore helps determine which variables are most significant. As the model results indicate, the processing rate is affected, impacting the capacity of the port and resulting in subsequent degradation in the processing time and throughput flow of the system. Ultimately, efficiency is affected, which is a major concern when dealing with the resiliency of the MTS when disrupted by a disaster.

This model can be used by the Port Authority and maritime shipping planners to manage the disruptive impacts of a natural disaster on the port system. The steps needed to return the port to pre-event capacity can be determined. This information is beneficial for maritime port engineering managers to plan and recommend best practices to mitigate storm damage and improve the resiliency of the system.

7. FUTURE WORK

This model is an initial step in understanding and demonstrating the causal relations of the flow of freight from the USA to the Port of San Juan, Puerto Rico, and how that flow is affected by a large disaster. The results presented here will allow further study of the behavior of the MTS and allow planners to better understand the impact on MTS performance as a result of damage caused by disaster disruption. There is interest in expanding the model to better understand a port’s ability to receive goods (i.e. tonnage resiliency) and to better determine how long it could take to transport goods (i.e. time resiliency). Refining these metrics will generate a better understanding of the impact of disaster disruptions on the MTS. This future work will help with decision-making strategies that will be beneficial for MTS stakeholders and provide policy makers with a competitive advantage when it comes to understanding the impact of natural disruptions and the resiliency of a system.

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II. A MODEL FOR THE EVALUATION OF ENVIRONMENTAL IMPACT INDICATORS FOR A SUSTAINABLE MARITIME TRANSPORTATION SYSTEM

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ABSTRACT

Maritime shipping is considered the most efficient, low-cost means for transporting large quantities of freight over significant distances. Never-the-less this efficiency comes with the cost of negative environmental and societal impacts. Environmental sustainability, therefore, is a pressing issue for maritime shipping management. There is increasing interest in maritime issues that affect the safety, security, air and water quality resulting from the movement of freight along the world's coast lines, across oceans, through inland waterways, and at port facilities. In depth studies of maritime transportation systems (MTS) can be used to identify key environmental impact indicators. This paper develops a tool for Decision Making in Complex Environments (DMCE) that will quantify and rank preferred environmental impact indicators within a MTS. Such a model will help decision makers achieve goals of improved environmental sustainability. The model will also provide environmental policy-makers in the shipping industry with an analytical tool that can evaluate tradeoffs

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within the system and identify possible alternatives to mitigate detrimental effects on the environment.

KEYWORDS

Environmental sustainability, maritime transportation system, environmental impact indicators, fuzzy analytic hierarchy process, fuzzy TOPSIS, decision-making tool

1. INTRODUCTION

Maritime transportation system, or MTS, consists of ports, and inter-modal land-side connections that allow various modes of transportation to move goods to, from and on the water. MTS transports about 90 percent of global trade (United Nations, 2016). Marine transport is considered the most efficient and cost-effective method for transportation of goods, providing a dependable means of facilitating commerce among nations (UNCTAD, 2012; IMO, 2012). However, MTS are also sources of environmental pollution; this produces new and critical challenges for port managers (Luo & Yip , 2013). According to the International Maritime Organization (IMO), maritime shipping was estimated to have accounted for 2.3 percent of global emissions of CO_2 in 2012, and it is estimated that these emissions will increase by 50 percent by year 2050 (OECD & PBL Netherlands Environmental Assessment Agency, 2012). The increasing demands on our MTS must be safely handled and balanced with environmental values, in order to ensure that freight move efficiently to, from, and on our waterfronts.

As container traffic increases, ports continue to increase in size and throughput in order to compete in global trade. Ideally, this growth should take place without imposing additional externalities that are harmful towards the environment. As such, it falls to the port authorities to take the initiative in finding ways to lessen environmental damage from their operations while enhancing performance (Melious, 2008). Hence it is essential for ports to adapt to twenty-first century concerns and implement best practices to reduce their environmental impact at both local and global levels.

De Toni and Comello (2005) define a system or phenomena as complex when it is made up of many components that interact in myriad ways, and whose behavior is highly dependent on these interactions. They also state that these interactions different levels; both their elements and these hierarchical levels are linked by a great variety of non-linear relationships, capable of exchanging stimuli with one another and with their environment. By this definition, the management of a maritime transportation system's supply chain is a highly complex problem, and a complex phenomenon that cannot be understood analytically. It cannot be analyzed component by component, but must be treated as a whole unit.. Although there is research addressing sustainability in maritime transportation systems, it is somewhat limited (IMO, 2012). There is a need for a more complete understanding of the environmental impact the industry has on local and global ecosystems in order to develop a sustainable protocol as MTS activity grows significantly in the near future. If the preferred environmental performance measures lack understanding from typical management reviewers in the marine industry, it will be difficult to evaluate the sustainability of the system (Johnson et al., 2013). For maritime transportation systems to function efficiently it is important to understand and address certain key performance environmental measures.

1.1 ENVIRONMENTAL SUSTAINABILITY

Environmental sustainability is a global issue that has been gathering momentum over the past decade (Carter & Rogers, 2008; Mudgal et al., 2010). It is triggered by the growing needs of an expanding world population and increasing economic activity which deplete natural resources and impose great pressure on the environment. As a result, the increasing demands on our MTS also must be safely handled and balanced with environmental values. Coordination, leadership, and cooperation between experts and decision-makers in the shipping industry are essential to address the challenges faced by the MTS. Information on safety, natural environment, and security must be shared among regional and local agencies, as well as private sector owners and operators, in order to effectively meet the needs of the MTS. As a consequence of this consensus, a green concept has emerged as a way to develop and operate marine activities that inhibits environmental degradation (Chiu et al., 2014). The green economy is seen as a vital policy option that can address the growing economic, environmental and social challenges.

A review of the maritime industry literature shows how important a comprehensive understanding of sustainability is for MTS efficiency. A port is considered sustainable if it finds an optimal balance between its performance as a business entity and its environmental impact (Broesterhuizen et al., 2014).

Studies published in recent years point to the importance of environmental sustainability as a topic among academic communities and the maritime industry (Chiu et al., 2014). The shipping industry keeps increasing its environmental awareness and requiring that their supply chain partners offer eco-efficient services as well (Lee & Lam, 2012). Most studies on maritime pollution focus on technical designs and operating issues and suggest control measures and goals to mitigate the environmental impact of specific ports (Johnson et al., 2013; Woo & Moon, 2013; Homsomba et al., 2013; Chang, 2013). Moreover, from a supply chain perspective, key performance measures for the environmental performance of the system are crucial to a system’s success and effectiveness. Therefore, the green port measures need further examination regarding their importance and priority for achieving environmentally-sustainable status.

In practice, the MTS cannot implement all sustainable measures existing in literature (Darbra et al., 2005; Chiu & Lai, 2011; Bailey & Solomon, 2004; Lirn et al., 2013; Peris-Mora et al., 2005) without compromising their efficiency and associated costs. Hence, there is a need to prioritize the most significant measures capable of attaining MTS sustainability.

Many reasons limit the possibility of continuous improvement towards a more sustainable environment in the maritime transportation industry. A survey study on the shipping industry has found that despite the necessity of identifying Key Performance Indicators (KPI), only 17 percent of the industry utilizes those KPI (Konsta & Plomaritou, 2012). The survey study has also found that out of all the performance problems found in the maritime industry, eight percent are directly attributed to the lack of understanding of environmental aspects (Konsta & Plomaritou, 2012). Although it is vital to determine the rank of those KPI in uncertain environments in order to improve the quality of the sustainable performance of the system, few studies focus on how port management can select the preferred environmental performance measures according to the importance of the greening factors (Peris-Mora et al., 2005; Lirn et al., 2013; Park & Yeo, 2012; Chiu & Lai, 2011; Puig et al., 2015).

As expressed previously, the research that focuses on developing indicators or frameworks that assess the MTS's sustainability is limited. Peris-Mora et al. (2005) proposed a system of sustainable environmental management indicators to be used by port authorities in order to analyze potential environmental impacts and risks with the use of a multi-criteria analysis technique. Their research used the Port of Valencia as reference. Lirn et al. (2013) applied an Analytic Hierarchy Process (AHP) to measure a port's green performance indicators and and used this(these) to evaluate the overall green performance of three major ports in Asia: Shanghai, Hong Kong and Kaohsiung. In their research, they study the weight and degree of performance of seventeen indicators under five dimensions: (1) air pollution management, (2) aesthetic and noise pollution management, (3) solid waste pollution management, (4) liquid pollution management, and (5) marine biology preservation. These dimensions were used to evaluate the greening of the ports. Park and Yeo (2012) implemented factor analysis and a fuzzy approach to create a Green Criteria of Seaport which consisted on fifteen indicators grouped into five main categories: (1) ease the environmental burden, (2) environment friendly method and technology development of construction, (3) utilization of resources and waste inside a port, (4) efficient planning and management of port operation, and (5) port redevelopment with introduction of waterfront concept. These criteria were utilized to evaluate the greenness of five major Korean ports. Chiu and Lai (2011) formulated a Fuzzy Analytic Hierarchy Process (FAHP) model which includes five dimensions and thirteen factors as the guidelines for green port operation. Results pointed out, after evaluating the operations of the three ports of Kaohsiung, Taichung and Keelung, that the top five priority attributes of green port operation are: hazardous waste handling, air pollution, water pollution, port greenery, and habitat quality maintenance. Finally, Puig et al. (2015) developed a computer-based tool to assist port authorities in identifying and assessing the Significant Environmental Aspects for the purpose of implementing effective environmental management of port operations.

1.2 PURPOSE OF STUDY

The scope of this paper includes the understanding of the environmental contributions those activities taking part in the MTS in ports and the travel to connections to move goods to, from and on the water have towards the performance of the MTS. Maritime transportation system is indispensable for a sustainable global economy, both in terms of energy efficiency and minimizing pollution. Environmental, social and economic dimensions of maritime transport are uniformly important and need to be addressed in any strategy, policy, regulatory framework or action concerning MTS (IMO, 2012). Limited research addressing environmental sustainability implies a gap in the general understanding of preferred metrics with which to evaluate environmental sustainability within MTS. Some of the existing studies including Peris-Mora et al. (2005), Lirn et al. (2013), Park and Yeo (2012) and Chiu and Lai (2011) are port specific and select the measures based on these specific ports, others discussed in the literature review section, fail to analyze uncertainty. This study addresses this gap by evaluating the preferred green performance measures by integrating fuzzy logic with a combination of Analytic Hierarchy Process (FAHP) and Techniques for Order Performance by Similarity to Ideal Solution (FTOPSIS). The integration of these methods (FAHP and FTOPSIS) is used to measure key performance indicators of MTS. This, then, leads to the development of a Decision-Making in Complex Environments (DMCE) tool for the evaluation of the preferred green measures in MTS. This helps understand the highly dependent interactions between MTS's activities and how they affect the environmental sustainability of the system.

2. METHOD

The evaluation of MTS sustainability is increasingly complicated. This is due, in part, to the many inter-related variables that are used to define a MTS model. Each variable has potential consequences that have to be predicted far into the future in order to quantify sustainability. Furthermore, the uncertainties associated with both the measurements of these variables and their predicted consequences are considerable, lending themselves to ‘Fuzzy” analyses. This leads to multiple operational, organizational and strategic management approaches to port systems, resulting in many discrepancies and uncertainties (Oguzitimur, 2011). These uncertainties may result from unquantifiable information or imprecise opinions and lead to the need to produce a comprehensive and structured port management discipline. In effect, key performance indicators (KPIs) are ranked based upon the experience of port managers, maritime experts (Tadic et al., 2016) or stakeholders in private industries. Such an *ad hoc* system makes the rankings very subjective and difficult to reproduce (Konsta & Plomaritou, 2012). Fuzzy, multi-criteria, decision-making methods have been developed specifically to handle such uncertain and subjective information more effectively than conventional multi-criteria decision-making methods. In multi-criteria decision analysis, the fuzzy set theory, introduced by Zadeh (1965), is considered the most common method when dealing with uncertainty (Demirel et al., 2008), particularly the uncertainty resulting from fuzziness in human judgment and preferences (Ding, 2011). Decision makers find more convenience and confidence dealing with interval judgments than with fixed-crisp values.

Expert preferences are difficult to quantify with certainty, which in turn makes it difficult to use as input to numerical models (Torfi et al., 2010). Therefore, fuzzy set theory provides a valuable tool, using linguistic variables that are translated into fuzzy numbers to generate decisions (Kahraman, 2009; Kaur and Chakrabortyb, 2007). Fuzzy numbers stand for a range of possible values applied to a particular variable, in consequence, what is expressed in vague and imprecise terms by the experts is treated by fuzzy set theory as a triangular probability distribution to be effectively used in logical reasoning and assist in making decisions (Figure 1). A single linguistic rating given by an expert will be transformed into a fuzzy number comprising multiple numbers that convey the range of possible values (Shukla et al., 2014). The mathematical concept as presented by (Hsieh at al., 2004) and (Liou et al., 2008) explains a fuzzy number A to have a triangular fuzzy number (TFN) distribution ($\mu_A(x)$) equal to Equation (1) (Balli and Korukoglu, 2009), where the TFN A is defined as a trio (l, m, u), representative of the lower bound or smallest possible value, the modal or most favorable value, and the upper bound or largest possible value, respectively, to describe the fuzzy number, A.

$$\mu_A(x/A) = \begin{cases} 0 & x < l; \\ \frac{x-l}{m-l} & l \leq x \leq m; \\ \frac{u-x}{u-m} & m \leq x \leq u; \\ 0 & x > u. \end{cases} \tag{1}$$

A geometric representation of the fuzzy number A from Equation (1) is shown in Figure 1, modified from Balli and Korukoglu (2009).

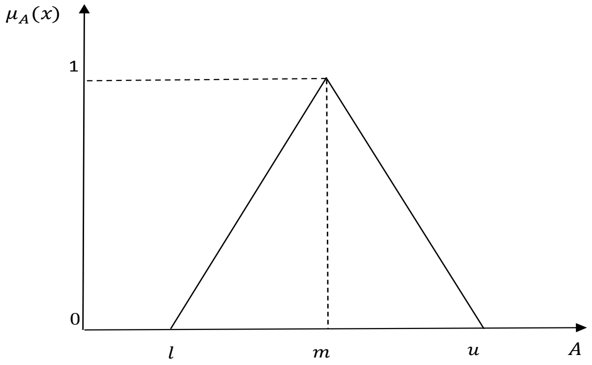

Figure 1. The Function of a Triangular Fuzzy Number A

A component of port efficiency and competitiveness is environmental port management (Lai et al., 2011). As such, it is important for shipping firms to take the initiative to find ways to lessen the environmental damages of their operations while at the same time enhancing their performance (Han, 2010) and identifying and satisfying the chief interests of the industry. In this paper, criteria are chosen to evaluate operational alternatives in terms of their environmental performance within the maritime transportation system (MTS). Table 1 shows a list of literature studies that influenced the criteria upon which alternative performance would be evaluated.

Table 1. List of Experts used for the Evaluation of Criteria and Alternatives

Expert	Source(s)
E1	Duru et al. (2012)
E2	Gudmundsson (2001)
E3	Lai et al. (2011)
E4	Peris-Mora et al. (2005)
E5	Jeon & Amekudzi (2005), Rodrigue et al. (2013)
E6	Lister (2015), Lun et al. (2016)

The selected six criteria and four alternatives used to evaluate the sustainability of MTS were chosen based on the review of many port authorities' green port measures and of earlier studies resulting in a synthesis of literature concerning the shipping industry, its key performance indicators (KPIs, and environmental sustainability (Kavakeb et al., 2015; Schinas and Stefanakos, 2012; Duru et al., 2013; Gudmundsson, 2001; Lai et al., 2011; Peris-Moraet al., 2005; Jeon & Amekudzi, 2005; Rodrigue et al., 2013; Lun et al., 2016; Lister, 2015; Yang et al., 2013; Shimin & Diew, 2012; UNCTAD , 2012; Lam, 2015; InterManager & MARINTEK, 2015). The criteria identified in the literature as having been the most repeated with highest weight of importance with solutions that lead to environmentally sustainable maritime transportation systems are presented in Table 2. These criteria permit the evaluation of the alternatives that are chosen to lead to a more sustainable maritime transportation system. These alternatives are presented in Table 3.

With the increase of environmental concerns with regards to maritime activity, the shipping industry needs to find a solution to attain environmental sustainability in their operations and the system as a whole. Along with regulatory requirements from institutions such as IMO, customers and stakeholders of shipping services are demanding environmental sustainability from the maritime services. Hence, the importance of this research when selecting the criteria and alternatives to be considered and evaluated, to make sure they integrate environmental concerns and practices into activities that firms or experts in the system take into consideration to evaluate the performance of the system. In the quest for environmental sustainability of MTS, there is a need to understand what the shipping managers and stakeholders expect and require from the system in environmental dimensions, and determine how those requirements can be translated into specific processes. For that reason, in this research, criteria are defined as those preferred environmental management requirements that allow the meeting of the goal, or in other words the set of preferred feasible solutions to the environmental sustainability performance issue. Alternatives are defined as those desired objectives that fit best with the goal of attaining environmental sustainability in the MTS or improving its environmental performance. In order to select the competitive alternatives and the determining criteria to be used for evaluation and to better support the decision-making process in the complex real-world of the maritime industry, a survey of literature related to the maritime industry was evaluated to detect patterns in discussed preferences amongst different reports and/or studies (Table 1).

The criteria from Table 2 are now described in more detail. (C1) Use of green design ships, engines and machinery is seen as a vital step for the shipping industry to address technical and economic aspects of using environmentally friendly shipping equipment and facilities. For example, new vessel design includes a waste-heat recovery system that reduces fuel consumption and CO_2 emissions by 9 percent along with a new designated space to be able to accommodate sulfur-cleaning scrubbers and enable the SO_2 to be removed before it is released into the atmosphere. The SO_2 that is captured in the scrubber is a recyclable product that can later be used as soil amendment in agriculture and in construction applications like cement (Romeo, 2013). (C2) Use of clean technologies such as low-sulfur fuel or alternate energy sources to fuel container ships, lead to higher fuel consumption efficiency and reduce CO_2 emissions (Peris-Mora et al., 2005). Alternatives to the heavy fuel oil which is presently used are needed to address environmental concerns and more stringent government regulations (Bengtsson et al., 2012). For instance, research performed has evaluated whether hybrid fuels, biofuels or even nuclear energy can be applied in shipping operations (Bengtsson et al., 2012; Dedes et al., 2012). (C3) Reuse and recycling of shipping-related wastes involves developing and implementation of recycling programs. These programs could include the storage of waste during transit and using green packing materials. Lai et al. (2011) suggest the sale or reuse of shipping materials and used oil as an insentive for implementing such sustainability programs. (C4) Ballast water treatment and residue/waste/spill control includes the managing of ship wastes during the voyage to prevent the disposal of wastes at sea. Installation of ballast water treatment systems on future ships will minimize the introduction of invasive species that threaten local ecosystems (Department of Homeland Security, 2012). (C5) Logistics and scheduling efficiency for the reduction of idle and waiting times is also attributed to environmental sustainability of the MTS (Lam, 2015) since it minimizes the environmental impacts and improves the environmental performance of the system. For example, optimized voyage planning can result in fuel savings, and identifying the most fuel-efficient route and engaging in a steady running strategy contributes to the reduction of emissions and the environmental performance of the system (Lai et al., 2011; Xin at al., 2014). Also, by reducing idle and wait times in port, the gaseaous and particulate emissions from vessels are reduced, thus improving air quality (Eyring, et al., 2010; Fagerholt et al., 2015). The last criteria is that of the usage of environmentally friendly shipping equipment and facilities (C6), which include those green practices adopted by the industry in order to improve environmental performance as well as economic competitiveness. For example, MTS engaging in green practices such as using non-toxic paint (Yang et al., 2013; Gudmundsson, 2001).

Table 2. Selected Criteria for the Evaluation of Environmental Performance Alternatives of Maritime Transportation Systems (MTS)

Notations	**Environmental Performance Criteria**
C1	Use of green design in ships, engines and machinery
C2	Use of clean technologies such as, low sulfur fuel and option to alternate energy (fuel type)
C3	Reuse and recycle of resources used in shipping
C4	Ballast water treatment and residue/waste/spill control
C5	Logistic and scheduling efficiency for such as reduction of idle and waiting times
C6	Use of environmentally friendly shipping equipment and facilities

Table 3. Environmental Performance Alternatives for Maritime Transportation Systems (MTS)

Notations	Environmental Performance Alternatives
A1	Reduction of release of substances as defined by MARPOL Annex 1-6
A2	Management of water ballast violations
A3	Contained spill of hazardous materials
A4	Reduction of environmental deficiencies

Table (3) depicts the four alternatives for a sustainable maritime transportation system, namely (A1) Reduction of release of substances as defined by International Convention for the Prevention of the Pollution from Ships (MARPOL) Annex 1 through 6, (A2) Management of ballast water violations, (A3) Containment of spills of hazardous materials, and (A4) Reduction of environmental deficiencies (Duru et al., 2013; Lam, 2015). These alternatives are specifically related to environmental sustainability, and are considered herein as major pathways promoting improved performance in MTS. The first alternative (A1) focuses on the pollution aspect of environmental sustainability, including air and water pollution with specific emphasis on reducing the release of waste substances as defined by the International Convention for the Prevention of Pollution from Ships or short for Marine Pollution (MARPOL) in Annex 1 through 6 (IMO, 1978):

1. MARPOL Annex I – Prevention of Pollution by Oil
2. MARPOL Annex II – Control of Pollution by Noxious Liquid Substance in Bulk
3. MARPOL Annex III – Prevention of Pollution by Harmful Substances Carried by Sea in Packaged Form
4. MARPOL Annex IV – Prevention of Pollution by Sewage from Ships
5. MARPOL Annex V – Prevention of Pollution by Garbage from Ships
6. MARPOL Annex VI – Prevention of Air Pollution from Ships

The second alternative (A2), the management of ballast water violations considers the discharges from ships that have a negative impact on the marine environment since a discharge typically contains a variety of biological materials such as plants, viruses, and bacteria, often non-native, that can cause extensive ecological and economic damage along with serious human health problems (Darbra et al., 2005; Eyring et al., 2010). The third alternative (A3), the containment of spills of hazardous materials can have devastating effects on the environment. Such spills can be toxic to marine life and stored for a long time in marine sediments as natural bioremediation is typically a slow process and anthropogenic remediation costly (Eyring et al., 2010). Likewise, the fourth alternative (A4), the reduction of environmental deficiencies is also a requirement on environmental performance, while also contributing to the social performance and human health conditions at local and global levels (Eyring et al., 2010; Lam, 2015; Chiu et al., 2014).

The first step of a Decision-Making in Complex Environments (DMCE) protocol is to set up a hierarchy system such as the one shown in Figure (2). This system is composed of several hierarchies and includes a goal, evaluating the preferred KPIs for a sustainable MTS, criteria, as shown in Table (2), and the decision alternatives to determine the preferred choice, as shown in Table (3).

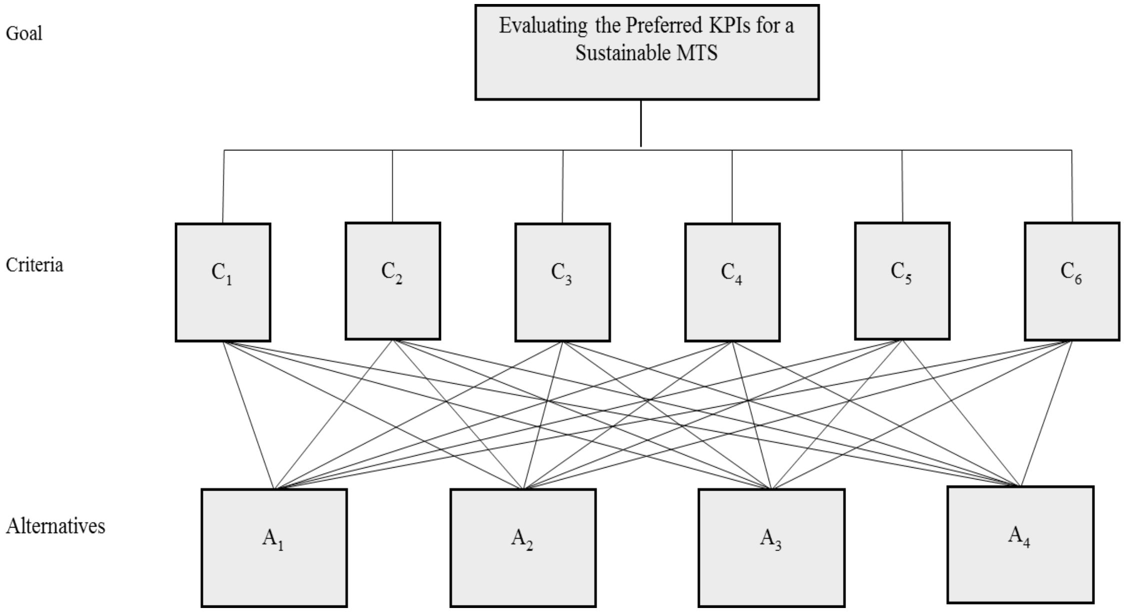

Figure 2. Decision-Making in Complex Environments (DMCE) model framework

The model proposed in this work is developed in two main steps: (1) the prioritization of weights for criteria using Fuzzy Analytic Hierarchy Process (FAHP) and

(2) the prioritizing of alternatives using Fuzzy Technique for Order Performance by Similarity to Ideal Solution (FTOPSIS) technique using the weights of criteria attained from FAHP. Basically, the DMCE tool consists of the integration of two methods. The intent of using FAHP is to compute important weight of the criteria that will be used in FTOPSIS method. In this work, an adaptation of Chang's (1992; 1996) extent analysis on FAHP is used.

2.1 FUZZY AHP

The following steps explain the process of determining priority weights for decision criteria:

Step 1: The collection of literature that will be used as the voice of the experts is selected as depicted in Table (1).

Step 2: The criteria is identified as shown in Table (2).

Step 3: The opinions and voice of the experts are utilized to provide the relative weight to each criteria conforming to the linguistic variables portrayed in Table (4) as defined by Tolga et al. (2005). The criteria are evaluated according to the experts by the selection of the related linguistic variables according to Table (4). The experts' comparisons of criteria by linguistic variable (by comparing which is the more important of each two criteria) were interpreted as illustrated in Table (5). Further, in order to proceed with the calculation of the pairwise comparison of criteria, the linguistic variables in Table (5) are converted into their corresponding TFNs, found in Table (4), resulting in Table (6) after combining Tables 4 and 5.

Table 4. Values of Triangular Fuzzy Numbers (TFN) (Tolga et al., 2005)

Linguistic Variables	Triangular Fuzzy Numbers	Reciprocal Triangular Fuzzy Numbers
Absolute (A)	(7/2, 4, 9/2)	(2/9, 1/4, 2/7)

Table 4. Values of Triangular Fuzzy Numbers (TFN) (Tolga et al., 2005) (cont.)

Linguistic Variables	Triangular Fuzzy Numbers	Reciprocal Triangular Fuzzy Numbers
Very Strong (VS)	(5/2, 3, 7/2)	(2/7, 1/3, 2/5)
Fairly Strong (FS)	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
Weak (W)	(2/3, 1, 3/2)	(2/3, 1, 3/2)
Equal (E)	(1, 1, 1)	(1, 1, 1)

Table 5. Pairwise Comparisons of Criteria via Linguistic Variables

Criteria	Experts	C1	C2	C3	C4	C5	C6
C1	**E1**	E	E	FS	VS	E	VS
	E2	E	W	W	W	VS	E
	E3	E	FS	FS	FS	A	E
	E4	E	E	E	W	FS	FS
	E5	E	W	E	W	E	E
	E6	E	W	W	E	W	E
C2	**E1**	E^{-1}	E	W	E	E	A
	E2	W^{-1}	E	VS	FS	VS	FS
	E3	FS^{-1}	E	FS	E	FS	E
	E4	E^{-1}	E	VS	FS	FS	VS
	E5	W^{-1}	E	FS	W	E	FS
	E6	W^{-1}	E	VS	VS	W	E
C3	**E1**	FS^{-1}	W^{-1}	E	E	W	W
	E2	W^{-1}	VS^{-1}	E	E	W	E
	E3	FS^{-1}	FS^{-1}	E	W	E	E
	E4	E^{-1}	VS^{-1}	E	E	FS	FS
	E5	E^{-1}	FS^{-1}	E	W	E	E
	E6	W^{-1}	VS^{-1}	E	W	W	W
C4	**E1**	VS^{-1}	E^{-1}	E^{-1}	E	E	FS
	E2	W^{-1}	FS^{-1}	E^{-1}	E	E	E
	E3	FS^{-1}	E^{-1}	W^{-1}	E	FS	E
	E4	W^{-1}	FS^{-1}	E^{-1}	E	VS	FS
	E5	W^{-1}	W^{-1}	W^{-1}	E	FS	E
	E6	E^{-1}	VS^{-1}	W^{-1}	E	E	E
C5	**E1**	E^{-1}	W^{-1}	W^{-1}	E^{-1}	E	A
	E2	VS^{-1}	W^{-1}	W^{-1}	E^{-1}	E	E
	E3	A^{-1}	E^{-1}	E^{-1}	FS^{-1}	E	E
	E4	FS^{-1}	FS^{-1}	FS^{-1}	VS^{-1}	E	VS
	E5	E^{-1}	E^{-1}	E^{-1}	FS^{-1}	E	FS
	E6	W^{-1}	W^{-1}	W^{-1}	E^{-1}	E	E

Table 5. Pairwise Comparisons of Criteria via Linguistic Variables (cont.)

Criteria	Experts	C1	C2	C3	C4	C5	C6
C6	**E1**	VS^{-1}	A^{-1}	W^{-1}	FS^{-1}	A^{-1}	E
	E2	E^{-1}	FS^{-1}	E^{-1}	E^{-1}	E^{-1}	E
	E3	E^{-1}	E^{-1}	E^{-1}	E^{-1}	E^{-1}	E
	E4	FS^{-1}	VS^{-1}	FS^{-1}	FS^{-1}	VS^{-1}	E
	E5	E^{-1}	FS^{-1}	E^{-1}	E^{-1}	FS^{-1}	E
	E6	E^{-1}	E^{-1}	W^{-1}	E^{-1}	E^{-1}	E

Step 4: Fuzzy important weight of criteria is calculated by employing the geometric mean of the experts' opinions. In order to be able to calculate the geometric mean, Buckley's (1985) geometric mean method is used and results are shown in Table (7).

Step 5: The fuzzy relative importance weight of the criteria is calculated using an adaptation of Chang's (1996) extent analysis method (equations 2-5).

Let $G = \{g_1, g_2, g_3, \ldots, g_n\}$ be a goal set. Each criteria is utilized and the extent analysis for each goal g_i is performed, respectively. Then, m extent analysis values for each criteria are attained using the following notation (Kahraman et al., 2004); $M_{g_i}^1, M_{g_i}^2, M_{g_i}^3, M_{g_i}^4, M_{g_i}^5, \ldots, M_{g_i}^m$, where g_i is the goal set $(i = 1,2,3,4,5, \ldots, n)$ and $M_{g_i}^j$ $(j = 1,2,3,4,5, \ldots, m)$, where all are TFNs.

The value of the fuzzy synthetic extent value (S_i) with respect to the ith criteria is defined as seen in Equation (2):

$$S_i = \sum_{j=1}^{m} M_{g_i}^j \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^j\right]^{-1} \tag{2}$$

Then, in order to obtain equation $\sum_{j=1}^{m} M_{g_i}^j$, the fuzzy addition operation (Sun, 2010) of m extent analysis values for a certain matrix occur as seen in Equation (3):

$$\sum_{j=1}^{m} M_{g_i}^j = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j\right) \tag{3}$$

Where l is the lower bound value, m the most promising value, and u the upper bound value. Then, to obtain $\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j}\right]^{-1}$, proceed to execute the fuzzy addition operation of $M_{g_i}^{j}$ $(j = 1,2,3,4,5, \dots, m)$ values using Equation (4):

$$\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j} = \left(\sum_{j=1}^{n} l_j, \sum_{j=1}^{n} m_j, \sum_{j=1}^{n} u_j\right) \tag{4}$$

And to calculate the inverse of the vector, use Equation (5):

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j}\right]^{-1} = \left(\frac{1}{\sum_{j=1}^{n} u_j}, \frac{1}{\sum_{j=1}^{n} m_j}, \frac{1}{\sum_{j=1}^{n} l_j}\right) \tag{5}$$

The resulting fuzzy synthetic extent with respect to its criteria are presented in Table (8).

Step 6: The defuzzification method presented in Equation (6) from Sun (2010) is applied in order to find the Best Non-Fuzzy Priority (BNP) or crisp weight value of criteria. After calculating the BNP value, one can proceed to rank the criteria in order of preference as presented in Table (9).

$$BNP_{S_i} = \frac{\left[\left(u_{S_i} - l_{S_i}\right) + \left(m_{S_i} - l_{S_i}\right)\right]}{3} + l_{S_i} \qquad where\ i = 1,2,3, \dots, 6 \tag{6}$$

To determine the fuzzy combination expansion for each criteria, first we calculate $\sum_{j=1}^{m} M_{g_i}^{j}$ value for each row of the matrix. For example, for C_1:

C_1= (1+ 0.874+ 1+ 1.018+ 1.435+ 1.246, 1+ 1.122+ 1.260+ 1.348+ 1.698+ 1.348, 1+1.427+ 1.554+ 1.758+ 1.973+ 1.435) = (6.573, 7.777, 9.147)

Then, the $\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j}$ value is calculated as: (6.573, 7.777, 9.147) ⊗ (7.529, 9.006, 10.589) ⊗ (4.636, 5.497, 6.576) ⊗, … , ⊗ (4.191, 4.540, 5.005) = (33.394, 38.725, 44.937).

Then, proceeded to calculate the $\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j}\right]^{-1}$ value

$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j}\right]^{-1}$= (1/44.937, 1/38.725, 1/33.394) = (0.022, 0.026, 0.030)

Table 6. Pairwise Comparisons of Criteria via TFNs

Criteria	Experts	C1	C2	C3
C1	**E1**	(1,1,1)	(1,1,1)	(3/2, 2, 5/2)
	E2	(1,1,1)	(2/3, 1, 3/2)	(2/3, 1, 3/2)
	E3	(1,1,1)	(3/2, 2, 5/2)	(3/2, 2, 5/2)
	E4	(1,1,1)	(1,1,1)	(1,1,1)
	E5	(1,1,1)	(2/3, 1, 3/2)	(1,1,1)
	E6	(1,1,1)	(2/3, 1, 3/2)	(2/3, 1, 3/2)
C2	**E1**	(1,1,1)	(1,1,1)	(2/3, 1, 3/2)
	E2	(2/3, 1, 3/2)	(1,1,1)	(5/2, 3, 7/2)
	E3	(2/5, 1/2, 2/3)	(1,1,1)	(3/2, 2, 5/2)
	E4	(1,1,1)	(1,1,1)	(5/2, 3, 7/2)
	E5	(2/3, 1, 3/2)	(1,1,1)	(3/2, 2, 5/2)
	E6	(2/3, 1, 3/2)	(1,1,1)	(5/2, 3, 7/2)
C3	**E1**	(2/5, 1/2, 2/3)	(2/3, 1, 3/2)	(1,1,1)
	E2	(2/3, 1, 3/2)	(2/7, 1/3, 2/5)	(1,1,1)
	E3	(2/5, 1/2, 2/3)	(2/5, 1/2, 2/3)	(1,1,1)
	E4	(1,1,1)	(2/7, 1/3, 2/5)	(1,1,1)
	E5	(1,1,1)	(2/5, 1/2, 2/3)	(1,1,1)
	E6	(2/3, 1, 3/2)	(2/7, 1/3, 2/5)	(1,1,1)
C4	**E1**	(2/7, 1/3, 2/5)	(1,1,1)	(1,1,1)
	E2	(2/3, 1, 3/2)	(2/5, 1/2, 2/3)	(1,1,1)
	E3	(2/5, 1/2, 2/3)	(1,1,1)	(2/3, 1, 3/2)
	E4	(2/3, 1, 3/2)	(2/5, 1/2, 2/3)	(1,1,1)
	E5	(2/3, 1, 3/2)	(2/3, 1, 3/2)	(2/3, 1, 3/2)
	E6	(1,1,1)	(2/7, 1/3, 2/5)	(2/3, 1, 3/2)
C5	**E1**	(1,1,1)	(2/3, 1, 3/2)	(2/3, 1, 3/2)
	E2	(2/7, 1/3, 2/5)	(2/3, 1, 3/2)	(2/3, 1, 3/2)
	E3	(2/9, 1/4, 2/7)	(1,1,1)	(1,1,1)
	E4	(2/5, 1/2, 2/3)	(2/5, 1/2, 2/3)	(2/5, 1/2, 2/3)
	E5	(1,1,1)	(1,1,1)	(1,1,1)
	E6	(2/3, 1, 3/2)	(2/3, 1, 3/2)	(2/3, 1, 3/2)
C6	**E1**	(2/7, 1/3, 2/5)	(2/9, 1/4, 2/7)	(2/3, 1, 3/2)
	E2	(1,1,1)	(2/5, 1/2, 2/3)	(1,1,1)
	E3	(1,1,1)	(1,1,1)	(1,1,1)
	E4	(2/5, 1/2, 2/3)	(2/7, 1/3, 2/5)	(2/5, 1/2, 2/3)
	E5	(1,1,1)	(2/5, 1/2, 2/3)	(1,1,1)
	E6	(1,1,1)	(1,1,1)	(2/3, 1, 3/2)

Table 6. Pairwise Comparisons of Criteria via TFNs (cont.)

Criteria	Experts	C4	C5	C6
C1	**E1**	(5/2, 3, 7/2)	(1,1,1)	(5/2, 3, 7/2)
	E2	(2/3, 1, 3/2)	(5/2, 3, 7/2)	(1,1,1)
	E3	(3/2, 2, 5/2)	(7/2, 4, 9/2)	(1,1,1)
	E4	(2/3, 1, 3/2)	(3/2, 2, 5/2)	(3/2, 2, 5/2)
	E5	(2/3, 1, 3/2)	(1,1,1)	(1,1,1)
	E6	(1,1,1)	(2/3, 1, 3/2)	(1,1,1)
C2	**E1**	(1,1,1)	(1,1,1)	(7/2, 4, 9/2)
	E2	(3/2, 2, 5/2)	(5/2, 3, 7/2)	(3/2, 2, 5/2)
	E3	(1,1,1)	(3/2, 2, 5/2)	(1,1,1)
	E4	(3/2, 2, 5/2)	(3/2, 2, 5/2)	(5/2, 3, 7/2)
	E5	(2/3, 1, 3/2)	(1,1,1)	(3/2, 2, 5/2)
	E6	(5/2, 3, 7/2)	(2/3, 1, 3/2)	(1,1,1)
C3	**E1**	(1,1,1)	(2/3, 1, 3/2)	(2/3, 1, 3/2)
	E2	(1,1,1)	(2/3, 1, 3/2)	(1,1,1)
	E3	(2/3, 1, 3/2)	(1,1,1)	(1,1,1)
	E4	(1,1,1)	(3/2, 2, 5/2)	(3/2, 2, 5/2)
	E5	(2/3, 1, 3/2)	(1,1,1)	(1,1,1)
	E6	(2/3, 1, 3/2)	(2/3, 1, 3/2)	(2/3, 1, 3/2)
C4	**E1**	(1,1,1)	(1,1,1)	(3/2, 2, 5/2)
	E2	(1,1,1)	(1,1,1)	(1,1,1)
	E3	(1,1,1)	(3/2, 2, 5/2)	(1,1,1)
	E4	(1,1,1)	(5/2, 3, 7/2)	(3/2, 2, 5/2)
	E5	(1,1,1)	(3/2, 2, 5/2)	(1,1,1)
	E6	(1,1,1)	(1,1,1)	(1,1,1)
C5	**E1**	(1,1,1)	(1,1,1)	(7/2, 4, 9/2)
	E2	(1,1,1)	(1,1,1)	(1,1,1)
	E3	(2/5, 1/2, 2/3)	(1,1,1)	(1,1,1)
	E4	(2/7, 1/3, 2/5)	(1,1,1)	(5/2, 3, 7/2)
	E5	(2/5, 1/2, 2/3)	(1,1,1)	(3/2, 2, 5/2)
	E6	(1,1,1)	(1,1,1)	(1,1,1)
C6	**E1**	(2/5, 1/2, 2/3)	(2/9, 1/4, 2/7)	(1,1,1)
	E2	(1,1,1)	(1,1,1)	(1,1,1)
	E3	(1,1,1)	(1,1,1)	(1,1,1)
	E4	(2/5, 1/2, 2/3)	(2/7, 1/3, 2/5)	(1,1,1)
	E5	(1,1,1)	(2/5, 1/2, 2/3)	(1,1,1)
	E6	(1,1,1)	(1,1,1)	(1,1,1)

The value of the fuzzy synthetic extent (S_i) with respect to ith criteria ($i = 1,2,3,4,5,6$) is calculated as seen in the example for criteria 1:

S_1= (6.573, 7.777, 9.147) ⊗ (0.022, 0.026, 0.030) = (0.146, 0.201, 0.274)

Lastly, to find the calculation of the best non-fuzzy priority (BNP) value of the fuzzy weights of each criteria takes place for all six criteria by using equation 6, calculated as follows for criteria 1:

$$BNP_{S_1} = \frac{[(0.274-0.146)+(0.201-0.146)]}{3} + 0.146 = 0.207$$

Table 7. Fuzzy Geometric Mean of Pairwise Comparison

Criteria	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**
C1	(1,1,1)	(0.874,1.122,1.427)	(1,1.260,1.554)	(1.018,1.348,1.758)	(1.435,1.698,1.973)	(1.246,1.348,1.435)
C2	(0.701,0.891,1.145)	(1,1,1)	(1.692,2.182,2.717)	(1.246,1.513,1.789)	(1.246,1.513,1.789)	(1.643,1.906,2.149)
C3	(0.644,0.794,1)	0.368,0.458,0.591)	(1,1,1)	(0.816,1,1.225)	(0.874,1.122,1.427)	(0.935,1.122,1.334)
C4	(0.569,0.742,0.983)	(0.559,0.661,0.802)	(0.816,1,1.225)	(1,1,1)	(1.334,1.513,1.672)	(1.145,1.260,1.357)
C5	(0.507,0.589,0.697)	(0.701,0.891,1.145)	(0.701,0.891,1.145)	(0.598,0.661,0.750)	(1,1,1)	(1.536,1.698,1.844)
C6	(0.697,0.742,0.802)	(0.465,0.525,0.609)	(0.750,0.891,1.070)	(0.737,0.794,0.874)	(0.542,0.589,0.651)	(1,1,1)

Table 8. Fuzzy Synthetic Extent with respect to its Criteria

Criteria	**Weight Low**	**Weight Med**	**Weight Upper**
C1	0.146	0.201	0.274
C2	0.168	0.233	0.317
C3	0.103	0.142	0.197
C4	0.121	0.159	0.211
C5	0.112	0.148	0.197
C6	0.093	0.117	0.150

Table 9. Best Non-Fuzzy Priority (BNP) or Crisp Values of Criteria

Criteria	BNP	Rank
C1- Green design	0.207	2
C2- Clean technologies	0.239	1
C3- Reuse and recycle	0.147	5
C4- Residue, waste and spill control	0.164	3
C5- Logistic and scheduling efficiency	0.152	4
C6- Green equipment and facilities	0.120	6

After the determination of the best non-fuzzy priority (BNP) value of the fuzzy weights of each criteria or the criteria weight, the second main step of this DMCE tool takes place by applying the prioritizing of alternatives using fuzzy Technique for Order Performance by Similarity to Ideal Solution (FTOPSIS) technique using these BNP weights of criteria attained from FAHP.

2.2 FUZZY TOPSIS

The TOPSIS technique was initially suggested by Hwang and Yoon (1981) and subsequently, the Fuzzy TOPSIS method was presented by Chen and Hwang (1992); and its basic concept is to prioritize the alternatives on the identified preferred criteria for improving MTSs sustainable performance. After finding the important weights of the criteria (BNP), FTOPSIS technique is used to rank the alternatives based on the closeness coefficients (CC). The method is based on the concept of selecting the best alternative, which has the shortest distance from the fuzzy positive-ideal solution (FPIS), and the longest distance from the fuzzy negative-ideal solution (FNIS). FTOPSIS explains a similarity index known as closeness coefficient (CC), which explains the nearness to the fuzzy positive-ideal solution and remoteness from the fuzzy negative-ideal solution. Resultant in a method for selecting the alternatives based on having the maximum similarity to the fuzzy positive-ideal solution (Hwang & Yoon, 1981) & (Chen & Hwang, 1992). The algorithm of the proposed FTOPSIS method is explained in the following steps as proposed by Chen (2000) and Chen et al (2006):

Step 1: The alternatives are identified as shown in Table (3).

Step 2: The opinions and voice of the experts are subjectively evaluated to give the relative weight to each alternative based on the linguistic variables portrayed in Table (10). The experts' comparisons of alternatives by linguistic variable (by comparing which is the more important of each two alternatives) are illustrated in Table (11). Further, in order to proceed with calculations these linguistic variables in Table (11) are converted into their corresponding TFNs found in Table (10) as defined by Shukla et al. (2014), and the results are presented in Table (12) after combining Tables 10 and 11.

Step 3: Construct the fuzzy decision matrix (FDM) depicted in Table (13) by determining the aggregated weight of alternatives with respect to each criteria by using Equation (7) as presented by Shukla et al. (2014):

$$FDM_E = (l_E, m_E, u_E) \qquad E = 1,2,3,\ldots,6 \tag{7}$$
$$l = min_E(l_E), \quad m = \frac{1}{E}\sum_{E=1}^{E} m\,, \quad u = max_E(u_E)$$

Where E represents the experts, as a trio (l, m, u), representative of the lower bound or smallest possible value, the modal or most favorable value, and the upper bound or largest possible value, respectively, that describe the TFN rating of all the experts. The resulting FDM is presented in Table (13).

Table 10. Linguistic Variables for Rating (Shukla et al., 2014)

Linguistic Variables	**Triangular Fuzzy Numbers**
Very Poor (VP)	(0 ,0, 2)
Poor (P)	(1, 2, 3)
Medium Poor (MP)	(2, 3.5, 5)
Fair (F)	(4, 5, 6)

Table 10. Linguistic Variables for Rating (Shukla et al., 2014) (cont.)

Linguistic Variables	**Triangular Fuzzy Numbers**
Medium Good (MG)	(5, 6.5, 8)
Good (G)	(7 ,8, 9)
Very Good (VG)	(8, 10, 10)

Table 11. Rating the Alternatives in Linguistic Terms

		Experts Rating					
Criteria	**Alternatives**	**E1**	**E2**	**E3**	**E4**	**E5**	**E6**
C1	**A1**	VG	VG	G	G	G	VG
	A2	F	P	M	M	P	F
	A3	G	G	M	VG	F	F
	A4	VG	G	VG	VG	G	G
C2	**A1**	VG	VG	VG	VG	G	VG
	A2	G	G	VG	VG	F	G
	A3	G	F	G	G	VG	G
	A4	VG	VG	G	G	G	VG
C3	**A1**	G	VG	VG	G	G	F
	A2	G	G	VG	G	VG	G
	A3	VG	G	M	G	G	G
	A4	G	G	G	VG	G	M
C4	**A1**	G	VG	G	G	M	VG
	A2	VG	VG	G	VG	G	VG
	A3	VG	G	G	G	VG	G
	A4	G	G	VG	G	VG	G
C5	**A1**	VG	G	G	VG	VG	G
	A2	VP	P	M	F	F	M
	A3	G	G	M	F	G	F
	A4	VG	G	G	M	VG	M
C6	**A1**	VG	G	VG	VG	G	VG
	A2	M	F	P	P	F	M
	A3	G	M	M	M	G	M
	A4	VG	G	G	M	VG	G

Table 12. Translating Linguistic Terms into Fuzzy Terms

		Experts Rating		
Criteria	**Alternatives**	**E1**	**E2**	**E3**
C1	**A1**	(8,10,10)	(8,10,10)	(7,8,9)
	A2	(4,5,6)	(1,2,3)	(2,3.5,5)
	A3	(7,8,9)	(7,8,9)	(2,3.5,5)
	A4	(8,10,10)	(7,8,9)	(8,10,10)
C2	**A1**	(8,10,10)	(8,10,10)	(8,10,10)
	A2	(7,8,9)	(7,8,9)	(8,10,10)
	A3	(7,8,9)	(4,5,6)	(7,8,9)
	A4	(8,10,10)	(8,10,10)	(7,8,9)
C3	**A1**	(7,8,9)	(8,10,10)	(8,10,10)
	A2	(7,8,9)	(7,8,9)	(8,10,10)
	A3	(8,10,10)	(7,8,9)	(2,3.5,5)
	A4	(7,8,9)	(7,8,9)	(7,8,9)
C4	**A1**	(7,8,9)	(8,10,10)	(7,8,9)
	A2	(8,10,10)	(8,10,10)	(7,8,9)
	A3	(8,10,10)	(7,8,9)	(7,8,9)
	A4	(7,8,9)	(7,8,9)	(8,10,10)
C5	**A1**	(8,10,10)	(7,8,9)	(7,8,9)
	A2	(0,0,2)	(1,2,3)	(5,6.5,8)
	A3	(7,8,9)	(7,8,9)	(5,6.5,8)
	A4	(8,10,10)	(7,8,9)	(7,8,9)
C6	**A1**	(8,10,10)	(7,8,9)	(8,10,10)
	A2	(2,3.5,5)	(4,5,6)	(1,2,3)
	A3	(7,8,9)	(2,3.5,5)	(2,3.5,5)
	A4	(8,10,10)	(7,8,9)	(7,8,9)

		Experts Rating		
Criteria	**Alternatives**	**E4**	**E5**	**E6**
C1	**A1**	(7,8,9)	(7,8,9)	(8,10,10)
	A2	(2,3.5,5)	(1,2,3)	(4,5,6)
	A3	(8,10,10)	(4,5,6)	(4,5,6)
	A4	(8,10,10)	(7,8,9)	(7,8,9)
C2	**A1**	(8,10,10)	(7,8,9)	(8,10,10)
	A2	(8,10,10)	(4,5,6)	(7,8,9)
	A3	(7,8,9)	(8,10,10)	(7,8,9)
	A4	(7,8,9)	(7,8,9)	(8,10,10)

Table 12. Translating Linguistic Terms into Fuzzy Terms (cont.)

		Experts Rating		
Criteria	**Alternatives**	**E4**	**E5**	**E6**
C3	**A1**	(7,8,9)	(7,8,9)	(8,10,10)
	A2	(7,8,9)	(8,10,10)	(7,8,9)
	A3	(7,8,9)	(7,8,9)	(7,8,9)
	A4	(8,10,10)	(7,8,9)	(2,3.5,5)
C4	**A1**	(7,8,9)	(5,6.5,8)	(8,10,10)
	A2	(8,10,10)	(7,8,9)	(8,10,10)
	A3	(7,8,9)	(8,10,10)	(7,8,9)
	A4	(7,8,9)	(8,10,10)	(7,8,9)
C5	**A1**	(8,10,10)	(8,10,10)	(7,8,9)
	A2	(4,5,6)	(4,5,6)	(5,6.5,8)
	A3	(4,5,6)	(7,8,9)	(4,5,6)
	A4	(5,6.5,8)	(8,10,10)	(5,6.5,8)
C6	**A1**	(8,10,10)	(7,8,9)	(8,10,10)
	A2	(1,2,3)	(4,5,6)	(2,3.5,5)
	A3	(2,3.5,5)	(7,8,9)	(2,3.5,5)
	A4	(5,6.5,8)	(8,10,10)	(7,8,9)

Table 13. Fuzzy Decision Matrix

	Alternatives			
Criteria	**A1**	**A2**	**A3**	**A4**
C1	(7,8,9)	(1,3.500,6)	(2,6.583,10)	(7,9,10)
C2	(7, 9.667,10)	(4,8.167,10)	(4,7.833,10)	(7,9,10)
C3	(7,9,10)	(7,8.667,10)	(2,7.583,10)	(2,7.583,10)
C4	(5,8.417,10)	(7,9.333,10)	(7,8.667,10)	(7,8.667,10)
C5	(7,9,10)	(0,4.167,8)	(4,6.750,9)	(5,8.167,10)
C6	(7,9.33,10)	(1,3.500,6)	(2,5,9)	(5,8.417,10)

Step 4: Calculate the weighted normalized fuzzy decision matrix (WNFDM) by using the criteria weights (BNP) attained from the FAHP by using equation (8) Shukla et al. (2014):

$$WNFDM = \left[fdm_{ij} * BNP\right]_{mxn} \quad i = 1,2, \dots, m \; and \; j = 1,2, \dots n \tag{8}$$

$$where \; fdm_{ij} = \left(\frac{l_{ij}}{C_j}, \frac{m_{ij}}{C_j}, \frac{u_{ij}}{C_j}\right) \; and \; C_j = \; max_i \; (FDM)$$

The resulting weighted normalized fuzzy decision matrix (WNFDM) is presented in Table (14).

Table 14. Weighted Normalized Fuzzy Decision Matrix

	Criteria					
Alternatives	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**
A1	(0.145,0.186,0.207)	(0.167,0.231,0.239)	(0.103,0.133,0.147)	(0.082,0.138,0.164)	(0.107,0.137,0.152)	(0.084,0.112,0.120)
A2	(0.021,0.072,0.124)	(0.096,0.195,0.239)	(0.103,0.128,0.147)	(0.115,0.153,0.164)	(0,0.064,0.122)	(0.012,0.042,0.072)
A3	(0.041,0.136,0.207)	(0.096,0.187,0.239)	(0.029,0.112,0.147)	(0.115,0.142,0.164)	(0.061,0.103,0.137)	(0.024,0.060,0.108)
A4	(0.145,0.186,0.207)	(0.167,0.215,0.239)	(0.029,0.112,0.147)	(0.115,0.142,0.164)	(0.076,0.124,0.152)	(0.060,0.101,0.120)

Step 5: Calculate the fuzzy positive-ideal solution (FPIS) and the fuzzy negative-ideal solution (FNIS) using equations (9) and (10), respectively as presented by Chen et al. (2006):

$$FPIS = (WFNDM_1^+, WFNDM_2^+, \dots, WFNDM_n^+) \tag{9}$$

$$\text{Where, } WFNDM_j^+ = max_i\{wfndm_{ij}\}$$

$$FNIS = (WFNDM_1^-, WFNDM_2^-, \dots, WFNDM_n^-) \tag{10}$$

$$\text{Where, } WFNDM_j^- = min_i\{wfndm_{ij}\}$$

$$i = 1,2, \dots, m\ ;\ \ j = 1,2, \dots, n$$

The resulting FPIS and FNIS for each criteria are presented in Table (15).

Step 6: Calculating the distance of each alternative from the FPIS and the FNIS as described by Shukla et al. (2014) in Equations (11) and (12), respectively:

$$d_i^+ = \sum_{j=1}^{n} d_v(wfndm_{ij} * wfndm_j^+)\ ;\ i = 1,2, \dots, m \tag{11}$$

$$d_i^- = \sum_{j=1}^{n} d_v(wfndm_{ij} * wfndm_j^-);\ i = 1,2, \dots, m \tag{12}$$

Where, d_v is the distance between two fuzzy numbers.

The resulting distances from the alternatives to the ideal solutions are provided in Table (16) for FPIS and Table (17) for FNIS.

Table 15. The Fuzzy Positive Ideal Solution (FPIS) and Fuzzy Negative Ideal Solution (FNIS) per Criteria

Criteria	FPIS	FNIS
C1	0.207	0.021
C2	0.239	0.096
C3	0.147	0.029
C4	0.164	0.082
C5	0.152	0.000
C6	0.120	0.012

Table 16. Distance between the Alternatives and the FPIS with respect to each Criteria

Distance	C1	C2	C3	C4	C5	C6	Sum
d(A1 to FPIS)	0.033	0.036	0.023	0.043	0.024	0.018	0.178
d(A2 to FPIS)	0.122	0.075	0.024	0.025	0.090	0.071	0.407
d(A3 to FPIS)	0.090	0.076	0.062	0.027	0.053	0.057	0.364
d(A4 to FPIS)	0.033	0.038	0.062	0.027	0.041	0.032	0.231

Table 17. Distance between the Alternatives and the FNIS with respect to each Criteria

Distance	C1	C2	C3	C4	C5	C6	Sum
d(A1 to FNIS)	0.139	0.105	0.087	0.050	0.116	0.082	0.578
d(A2 to FNIS)	0.058	0.087	0.085	0.057	0.069	0.034	0.389
d(A3 to FNIS)	0.110	0.085	0.072	0.053	0.091	0.054	0.465
d(A4 to FNIS)	0.139	0.100	0.072	0.053	0.106	0.074	0.544

Step 7: Rank the alternatives according to the closeness coefficients (CC) where the CC can be calculated for each alternative using Chen (2000) equation presented in Equation (13):

$$CC_i = \frac{d_i^-}{d_i^- + d_i^+} \quad ; i = 1,2, \dots, m. \tag{13}$$

The ranks based on each alternative’s closeness coefficient can be observed in Table (18). The closeness coefficient represents the distance from each alternative to the FPIS and the FNIS.

Table 18. Closeness Coefficient of Alternatives and their respective Ranking

Alternative	d^+	d^-	$d^+ + d^-$	CC	Rank
A1- Reduction release of substances: MARPOL	0.178	0.578	0.755	0.765	1
A2- Manage of water ballast violations	0.407	0.389	0.796	0.489	4
A3- Contained spill of hazardous materials	0.364	0.465	0.830	0.561	3
A4- Reduction of environmental deficiencies	0.231	0.544	0.775	0.702	2

3. DISCUSSION OF RESULTS

The activities in MTS are sources of environmental pollution, creating new and critical challenges to port managers. One such challenge is the need to reduce environmental damage while enhancing system performance. Although, multi-criteria decision methods have been implemented to assess these externalities, these methods have limitation in dealing with the imprecise nature of linguistic assessment. Decision-makers face uncertainties from those subjective perceptions and experiences in the decision-making process. To overcome these limitations, fuzzy multi-criteria decision-making methods have been implemented into this research work.

The need to understand which alternative strategies would most significantly enhance the MTS sustainability led to the integration of the Fuzzy AHP and Fuzzy TOPSIS methods. The FAHP was used to calculate the relative weights of each criteria in Table (2) and then, FTOPSIS was used to prioritize the MTS's sustainable alternatives in Table (3) based on these selection criteria.

This research ranked four alternative methodologies to promote sustainability based upon six criteria. As a result, FAHP determined the most important criteria to be C2, the use of clean technologies such as, low sulfur fuel or an alternate energy source, since had the highest weight or BNP (0.239). C1, the use of green design ships, engines and machinery, was ranked as the second highest criteria with a close weight or BNP of 0.207. Followed by, C4, ballast water treatment and residue/water/spill control with a BNP of 0.164, C5, logistics and scheduling efficiency for reduction of idle and waiting times with a BNP of 0.152, C3, reuse and recycle of resources on board with a BNP of 0.147 and, C6, the usage of environmentally friendly shipping equipment and facilities with a BNP of 0.120. The results for C2 and C1 are not surprising as one of the main targeted issues for improving the environmental sustainability is the reduction and control of pollution due to emissions. Furthermore, such a reduction and control of pollution is mainly driven by reducing water pollution and this directly relates to the third ranked criteria, C4.

Once the criteria weights had been established, it was then possible to evaluate the alternatives using FTOPSIS method. The ranking order of the four alternatives evaluated is as follows: A1 > A4 > A3 > A2. A1, the reduction of release of substances as defined by MARPOL Annex 1-6 received a closeness coefficient of 0.765. A4, the reduction of environmental deficiencies attained a closeness coefficient of 0.702. The latter two, A3, the controlled spills of hazardous materials and A2, the management of ballast water violations, received the lowest closeness coefficient values 0.561 and 0.489, respectively. A1 was the preferred alternative, presumably because it reduces air and water pollution simultaneously. A1 represents a broader scope in terms of the assessment of environmental externalities resulting from maritime activities that are detrimental to the environment. The second alternative (A4) represents system environmental performance by measuring the number of environmental-related deficiencies recorded relative to the total number of external inspections and audits. This alternative measures the importance of complying with regulations and policies when trying to increase environmental performance of MTS.

The determination of which alternatives have the most influence on the environmental performance of the maritime industry is recorded in their relative ranking. This would allow decision-makers and managers in the industry to develop a plan that improves the sustainable environmental performance of the MTS.

4. CONCLUSIONS AND FUTURE WORK

This research develops a Decision Making in Complex Environments (DCME) tool that quantifies and ranks preferred environmental impact indicators within a MTS. The model helps decision makers achieve environmental sustainability and also provide environmental policy-makers in the shipping industry with an analytical tool that can evaluate tradeoffs within the system and identify possible alternatives to mitigate detrimental effects on the environment. The integrated evaluation tool developed in this research (DMCE) uses FAHP and FTOPSIS methodologies and can provide marine decision-makers with a fuzzy analysis of traditional performance evaluation model that includes the uncertainty and imprecision that comes with decision-making in complex environments. The proposed method enables decision analysts in the maritime industry to better understand the complete evaluation process of alternatives and criteria for a sustainable system.

This study fills a gap by evaluating the preferred green performance measures by integrating fuzzy logic into the combination of Analytic Hierarchy Process (AHP) and the Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) methods, to measure the key performance indicators of a maritime transportation system with regards to the environment. Consequently, this research developed a Decision-Making in Complex Environments (DMCE) tool for evaluating the preferred green measures in the MTS. Moreover, the DMCE tool helps eliminate that portion of complexity that reduces the MTS’s performance, and attempts to get a better understanding on the beneficial elements and performance measures that positively impact the system’s environmental performance.

For future work, we propose to expand the model and evaluate the alternatives with respect to more detailed criteria. Also, since results of this research are based on the criteria and alternatives identified through examination and surveying of related literature, the testing and validation of the DMCE tool is limited to the experiences and knowledge of those chosen as experts. The incorporation of a greater number of experts could yield more accurate results with respect to the preferred green performance measures in the maritime industry to attain an environmentally sustainable system.

Moreover, the comprehensive methodology developed in this research can be implemented to evaluate other systems and infrastructures. This will allow decision makers to identify those preferred performance indicators in order to make strategic decisions and enhance the efficient and environmental performance of the maritime system.

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III. MONTE CARLO SIMULATION TO ANALYZE KEY ENVIRONMENTAL IMPACTS OF MARITIME TRANSPORTATION SYSTEM

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ABSTRACT

Maritime transportation system, or MTS, consists of ports, and inter-modal land-side connections that allow various modes of transportation to move goods to, from and on the water. The reliability on an effective and efficient MTS to serve the interest of stakeholders and further enhance global leadership and competitiveness, keeps gaining momentum as MTS transports about 90 percent of global trade (United Nations, 2016). They are considered the most efficient and cost-effective method for the international transportation of goods, providing a dependable means of facilitating commerce among nations (UNCTAD, 2012; IMO, 2012). However, MTS is also a source of environmental pollution through its activities, which produce new and critical challenges to port managers (Luo & Yip , 2013). This study adds a Monte Carlo simulation model to a previously developed Decision Making in Complex Environments (DMCE) tool (Pérez Lespier et al., 2017) that quantifies and ranks preferred environmental impact indicators within a MTS. The Monte Carlo simulation adds a better understanding to those risks associated with the ranking of preferred environmental indicators and assists decision makers to achieve goals of improved environmental sustainability.

KEYWORDS

Sustainability; maritime transportation system; environmental impact indicators; decision-making; Monte Carlo simulation; risk analysis

1. INTRODUCTION

Maritime transportation system, or MTS, plays a vital role in international supply chains since container terminals are crucial crossing points to transfer and distribute containers all over the world. MTS carries about 90 percent of world trade goods (United Nations, 2016). MTS is considered the most efficient and cost-effective method for the international transportation of goods, providing a reliable means of facilitating commerce between nations (UNCTAD, 2012; IMO, 2012). However, MTS is also a source of environmental pollution through its activities, which produce new and critical challenges to port managers (Luo & Yip , 2013).

The management of the maritime transportation system's supply chain is a highly complex problem; a complex phenomenon that cannot be understood analytically, but it has to be looked at as a system that cannot be divided. One of MTS's biggest concerns is its environmental impact. Although there is research addressing sustainability in maritime transportation systems, it is somewhat limited (IMO, 2012). Therefore the need for a more comprehensive understanding of the environmental impact MTS has on local and global ecosystems in order to develop a sustainable protocol as MTS activity is expected to increase significantly in the near future. If the preferred environmental performance measures lack understanding from typical management reviewers in the marine industry, and are not clearly understood, it makes it a difficult task to evaluate the sustainability of the system (Johnson et al., 2013). For maritime transportation systems to function efficiently it is important to understand and address certain key performance environmental measures. These key performance measures will help achieve sustainability and enhance system competitiveness.

Environmental sustainability is a global issue that has been gathering momentum over the last decade (Carter and Rogers, 2008; Mudgal et al., 2010). It is as a result of the growing needs of an expanding world population and increasing economic activity which deplete natural resources and impose great pressure on the environment. The increasing demands on our MTS also must be safely handled and balanced with environmental values, in order to ensure that freight moves efficiently to, from, and on our waterfronts. Coordination, leadership, and cooperation are essential to addressing the challenges faced by the MTS. Information on safety, natural environment, and security must be shared among regional and local agencies, as well as private sector owners and operators, in order to effectively meet the needs of the MTS while taking into consideration its environmental impacts. As a consequence of this consensus, a green concept has emerged as a way to develop and operate marine activities that inhibits environmental degradation (Chiu et al., 2014). The green economy is seen as a vital policy option that can address the growing economic, environmental and social challenges.

Many reasons limit the possibility of continuous improvement towards a more sustainable environment in the shipping industry. Studies have found that despite the necessity of identifying Key Performance Indicators (KPI), only 17 percent of the industry utilizes those KPI (Konsta and Plomaritou, 2012). Studies have also found that out of all the performance problems found in the maritime industry, eight percent are directly attributed to the lack of understanding of environmental aspects (Konsta and Plomaritou, 2012). Although it is vital to determine the rank of those KPI in uncertain environments in order to improve the quality of the sustainable performance of the system, only a few studies focus on how port management can select the preferred environmental performance measures according to the importance of the greening factors (Peris-Mora et al., 2005; Lirn et al., 2013; Park and Yeo, 2012; Chiu and Lai, 2011; Puig et al., 2015). If the preferred environmental performance measures are not clearly understood, it will be difficult to evaluate the sustainability of the system (Johnson et al., 2013). For maritime transportation systems to function efficiently it is important to understand and address certain key performance environmental measures. These key performance measures will help achieve sustainability and enhance a system’s competitiveness. The decision-making and optimization problems regarding uncertainty can be tackled generally by either analytical or simulation approaches (Steenken et al., 2004; Stahlbock and VoB, 2008). In this research, a Monte Carlo simulation is incorporated into a Decision-Making in Complex Environments (DMCE) tool (Pérez Lespier et al., 2017) in order to have a better understanding of the risks associated with the resulting decisions about the preferred environmental indicators to evaluate the sustainability of MTS.

1.1 PURPOSE OF STUDY

The scope of this paper includes the understanding of the risks associated with the selected metrics and activities evaluated to understand and address environmental sustainability in Maritime Transportation System (MTS). Maritime transportation system is indispensable in a sustainable future global economy, both in terms of energy efficiency and minimizing pollution. Environmental, social and economic dimensions of maritime transport are uniformly important and should be entirely recognized as such in any strategy, policy, regulatory framework or action (IMO, 2012). In order to address environmental sustainability, it is vital to understand the risks associated with those preferred metrics with which to evaluate environmental sustainability within MTS. Pérez Lespier et al., 2017, developed a Decision-making in Complex Environments (DMCE) tool which integrates fuzzy theory to analyze the uncertainty that comes along from those subjective perceptions and experiences in the decision-making process, especially in multi-criteria decision methods. The study evaluates the preferred green performance measures by integrating fuzzy logic with a combination of Analytic Hierarchy Process (FAHP) and Techniques for Order Performance by Similarity to Ideal Solution (FTOPSIS). The integration of these methods (FAHP and FTOPSIS) is used to measure key performance indicators of MTS. The DMCE tool allows the evaluation of the preferred green measures in MTS and helps understand the highly dependent interactions between MTS activities and how they affect the environmental sustainability of the system. In order to complement the analysis of the DMCE tool, a Monte Carlo simulation was incorporated into the tool to better understand the risks associated with the resulting rankings of those preferred environmental indicators. The Monte Carlo simulation enhances the tool by yielding the probabilities or risks associated with the ranking of each of the criteria and alternatives evaluated. This model assists decision-makers in the maritime industry with a better understanding of the tradeoffs within the rankings of the criteria and the alternatives preferred for a sustainable MTS.

2. METHOD

The evaluation addressing sustainability in MTS is increasingly complicated. This is due, in part, to the many inter-related variables that are used to define a model of MTS. Each variable has potential consequences that have to be predicted far into the future in order to quantify sustainability. Furthermore, the uncertainties associated with both the measurements of these variables and their predicted consequences are considerable, imparting themselves to ‘Fuzzy” analyses. This tends to lead to multiple operational, organizational and strategic management approaches to port systems, resulting in many discrepancies and uncertainties (Oguzitimur, 2011). These uncertainties may result from unquantifiable information or imprecise opinions and lead to the need to produce a comprehensive and structured port management discipline. In effect, key performance indicators (KPIs) are ranked based upon the experience of port managers, maritime experts (Tadic, et al., 2016) or stakeholders in private industries. Such an *ad hoc* system makes the rankings very subjective and difficult to reproduce (Konsta & Plomaritou, 2012). Fuzzy, multi-criteria, decision-making methods have been developed specifically to handle such uncertain and subjective information more effectively than conventional multi-criteria decision-making methods. In multi-criteria decision analysis, the fuzzy set theory, introduced by Zadeh (1965), is considered the most common method when dealing with uncertainty (Demirel et al., 2008), particularly the uncertainty resulting from fuzziness in human judgment and preferences (Ding, 2011). Decision makers find more convenience and confidence dealing with interval judgments than with fixed-crisp values.

By calculating the risk associated with these decision-making, it results in a clearer depiction of the consequences of each action considered to address sustainability in MTS.

A component of port efficiency and competitiveness is environmental port management (Lai et al., 2011). Fundamentally, it is important for shipping firms to take the initiative to find ways to lessen the environmental damages of their operations while at the same time enhancing their performance (Han, 2010) and identifying and satisfying the chief interests of the industry. In this paper, criteria are chosen to evaluate operational alternatives in terms of their environmental performance within the maritime transportation system (MTS). Table 1 shows a list of literature studies that influenced the criteria upon which alternative performance would be evaluated.

Table 1. List of Experts used for the Evaluation of Criteria and Alternatives (from Pérez Lespier et al., 2017)

Expert	Source(s)
E1	Duru et al. (2012)
E2	Gudmundsson (2001)
E3	Lai et al. (2011)
E4	Peris-Mora et al. (2005)
E5	Jeon & Amekudzi (2005), Rodrigue et al. (2013)
E6	Lister (2015), Lun et al. (2016)

From Pérez et al., 2017, the criteria identified in the literature as having been the most repeated with highest weight of importance with solutions that lead to environmentally sustainable maritime transportation systems are presented in Table 2. These criteria permit the evaluation of the alternatives that are chosen to lead to a more sustainable MTS, these alternatives are presented in Table 3.

Due to the increase of environmental concerns with regards to maritime activity, the shipping industry needs to find a solution to attain environmental sustainability in their operations and the system as a whole and understand the risk associated with the different components that this solution entails. Along with regulatory requirements from institutions such as International Maritime Organization (IMO), customers and stakeholders of shipping services are demanding for environmental sustainability from the maritime services.. For that reason, Pérez et al, 2017 in their research, criteria were defined as those preferred environmental management requirements that allow the meeting of the goal, or in other words the set of preferred feasible solutions to the environmental sustainability performance issue. Alternatives were defined as those desired objectives that fit best with the goal of attaining environmental sustainability in the MTS or improving its environmental performance. In order to select the competitive alternatives and the determining criteria to be used for evaluation and to better support the decision-making process in the complex real-world of the maritime industry, a survey of literature related to the maritime industry was evaluated to detect patterns in discussed preferences amongst different reports and/or studies presented in Table 1.

Table 2. Selected criteria for the Evaluation of Environmental Performance Alternatives of Maritime Transportation System (MTS) (from Pérez Lespier et al.,2017)

Notations	**Environmental Performance Criteria**
C1	Use of green design in ships, engines and machinery
C2	Use of clean technologies such as, low sulfur fuel and option to alternate energy (fuel type)
C3	Reuse and recycle of resources used in shipping
C4	Ballast water treatment and residue/waste/spill control
C5	Logistic and scheduling efficiency for such as reduction of idle and waiting times
C6	Use of environmentally friendly shipping equipment and facilities

Table 3. Environmental Performance Alternatives for Maritime Transportation System (MTS) (from Pérez Lespier et al., 2017)

Notations	**Environmental Performance Alternatives**
A1	Reduction of release of substances as defined by MARPOL Annex 1-6
A2	Management of water ballast violations
A3	Contained spill of hazardous materials
A4	Reduction of environmental deficiencies

The model proposed by Pérez Lespier et al., 2017 was developed in two main steps: (1) the prioritization of weights for criteria using Fuzzy Analytic Hierarchy Process (FAHP) and (2) the prioritizing of alternatives using Fuzzy Technique for Order Performance by Similarity to Ideal Solution (FTOPSIS) technique using the weights of criteria attained from the FAHP in step 1. Essentially, the DMCE tool consists of the integration of the methods of FAHP and FTOPSIS. The intent of using FAHP is to compute important weight of the criteria that will be used in FTOPSIS method. Still there is need in the understanding of risk associated with the outcome of the DMCE tool's rankings of the criteria and alternatives being considered for a sustainable performance in the MTS. Therefore, in this research Monte Carlo simulation is integrated to the DMCE tool in order to account for that risk in the quantitative analysis and decision-making.

2.1 MONTE CARLO SIMULATION

For effective environmental decision-making to take place, it is key for predictive tools to be accurate and robust (Wood et al., 2015). Monte Carlo (MC) simulation is a systematic approach for decision-making under uncertainty and a powerful tool for providing advice on the probabilities of occurrence given the available information (Polasky et al., 2011).

Monte Carlo (MC) simulation, or probability simulation, is a technique used to understand the impact of risk and uncertainty in models. MC allows the observation of possible outcomes of decisions and consequently, assesses the impact of risk, allowing for better decision-making under uncertainty (Metropolis and Ulam, 1949). MC simulation allows for the analyzing of uncertainty propagation, where the goal is to determine how random variation, differences in input of knowledge, or error affects the sensitivity, performance, or reliability of the system that is being modeled (Metropolis & Ulam, 1949).

MC simulation is a method that solves a problem by generating suitable random numbers and observing what fraction of the numbers are obeying some defined property. This method is useful for obtaining numerical solutions to problems which are too complicated to solve analytically. By using a range of possible values, instead of a single guess, a more realistic picture and understanding can be attained with regards to the risk and uncertainty in the model. In a MC simulation, random samplings are performed in order to conduct a large number of experiments on a computer. Then, the statistical characteristics of the experiments (model outputs) are observed, and conclusions on the model outputs are drawn based on the statistical experiments. In each experiment, the possible values of the input random variables $X = \{x_1, x_2, x_3, \dots, x_n\}$ are generated according to the distributions they follow. Then, the values of the output variable Y_n are calculated through the performance function $Y = \{g(x)\}$ at the samples of input random variables following their respective calculated distributions. The MC simulation will run a number of experiments carried out in this manner, allowing for a set of samples of Y to be available for the statistical analysis, which will ultimately estimate the characteristics of the output variable Y, which help describe the risk in the model (Metropolis & Ulam, 1949). The direct results of Monte Carlo simulation are absolutely necessary for making defensible decisions and for managing risks. Probability distributions give the full range of possible outcomes, or how likely those outcomes are to occur, and identifies those items that impact your model most significantly and by how much.

2.2 MODEL

Adapted from (Metropolis & Ulam, 1949), the general outline of the MC simulation used in this research is depicted in Figure 1, where the inputs are linguistic variables translated into triangular fuzzy numbers (TFN) which the experts provided as input into the pairwise comparisons of the criteria and alternatives evaluated in the DMCE tool (Pérez et. al., 2017). Three steps are required in the MC simulation process (Metropolis & Ulam, 1949): Step 1: sampling of the experts input into the pairwise comparisons (input variables X) occurs for a set number of one thousand times after their respective distributions (per expert per evaluation were determined), Step 2: evaluating model output Y, which in this research would be which in this research would be the yielded ranks for the criteria and alternatives being evaluated, and Step 3: statistical analysis on model output, which is the evaluation on the probabilities or likelihood of occurrence of the evaluated criteria and alternatives.

The Monte Carlo simulation is a virtual experiment repeated one thousand times in this research in this research, all while generating random samples of the experts' inputs into the pairwise comparisons of criteria and alternatives evaluated in the DMCE tool, bound by the set parameters defined by the attained distribution for each sample evaluated from each repetition of that experiment. Then, those samples are transformed into the inverse of their respective distributions and bounded by the parameters with a minimum value of 0 and maximum values of 4.5 and 10 for the FAHP and FTOPSIS, respectively. Those values used to set the maximum and minimum range boundaries were attained from the maximum of the TFN used to translate the experts' input as utilized in the DMCE tool developed by Pérez Lespier et al., 2017. Those random samples are then collected, organized and analyzed to understand the behavior of that complex process or system. This results in better decision-making resulting from a better understanding of the probabilities or likelihood of occurrence of the evaluated criteria and alternatives. Ultimately, this provides a better understanding of the different possible scenarios and the likelihood that they will occur. For example, to be able to calculate the probability that C1 would be ranked 1, the probability that C1 would be ranked 2, and so forth.

Figures 2 and 3 depict the frameworks on how the MC simulation was incorporated into the FAHP and FTOPSIS portions of the DMCE tool, respectively. After incorporating the MC simulation into the DMCE tool the results of the risk of ranking the evaluated criteria and alternatives can be analyzed. Figure 4 depicts a sample of the outcomes yielded from the MC simulation incorporated into the FAHP portion of the DMCE tool. As observed in the sample figure, the MC simulation ran one thousand experiments or iterations, which yielded the Best Non-Fuzzy Priority (BNP) or crisp weight value of criteria for each of the six criteria evaluated in the FAHP of the DMCE tool. After calculating the BNP value, proceeds the ranking of each of the sixth criteria, for each experiment or iteration. Follows, a quantification of and a more comprehensive view of how likely are these criteria to be in the different rankings by calculating the respective probability of each criteria of being ranked in each of the six positions. A more thorough discussion of these possible outcomes takes place in the *Discussion of Results* section.

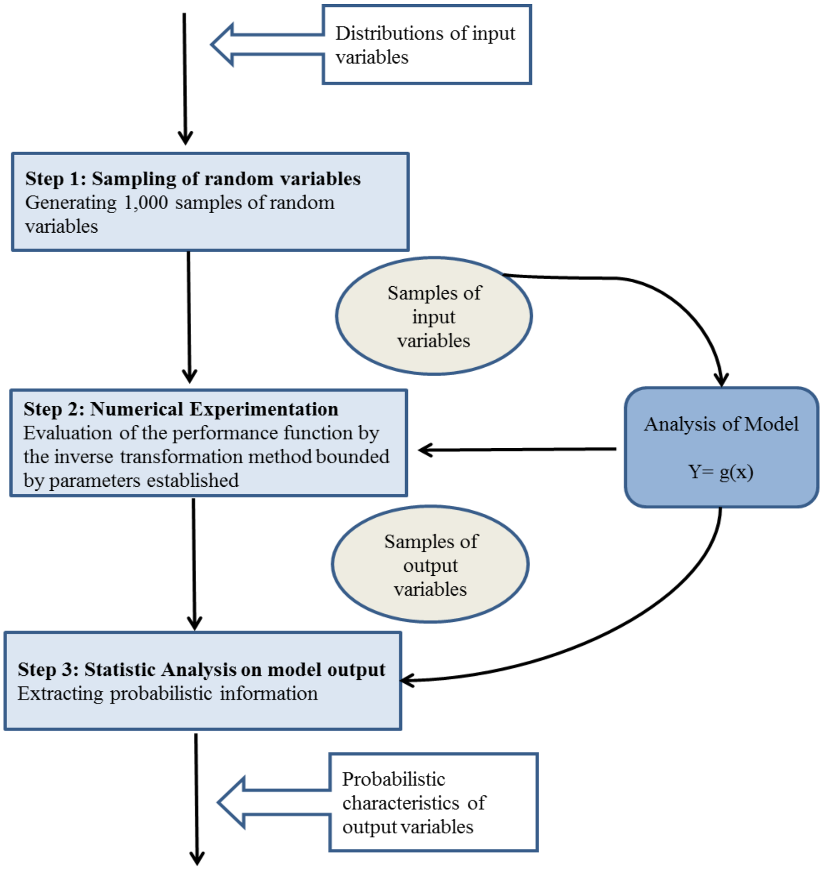


Figure 1. Monte Carlo Simulation

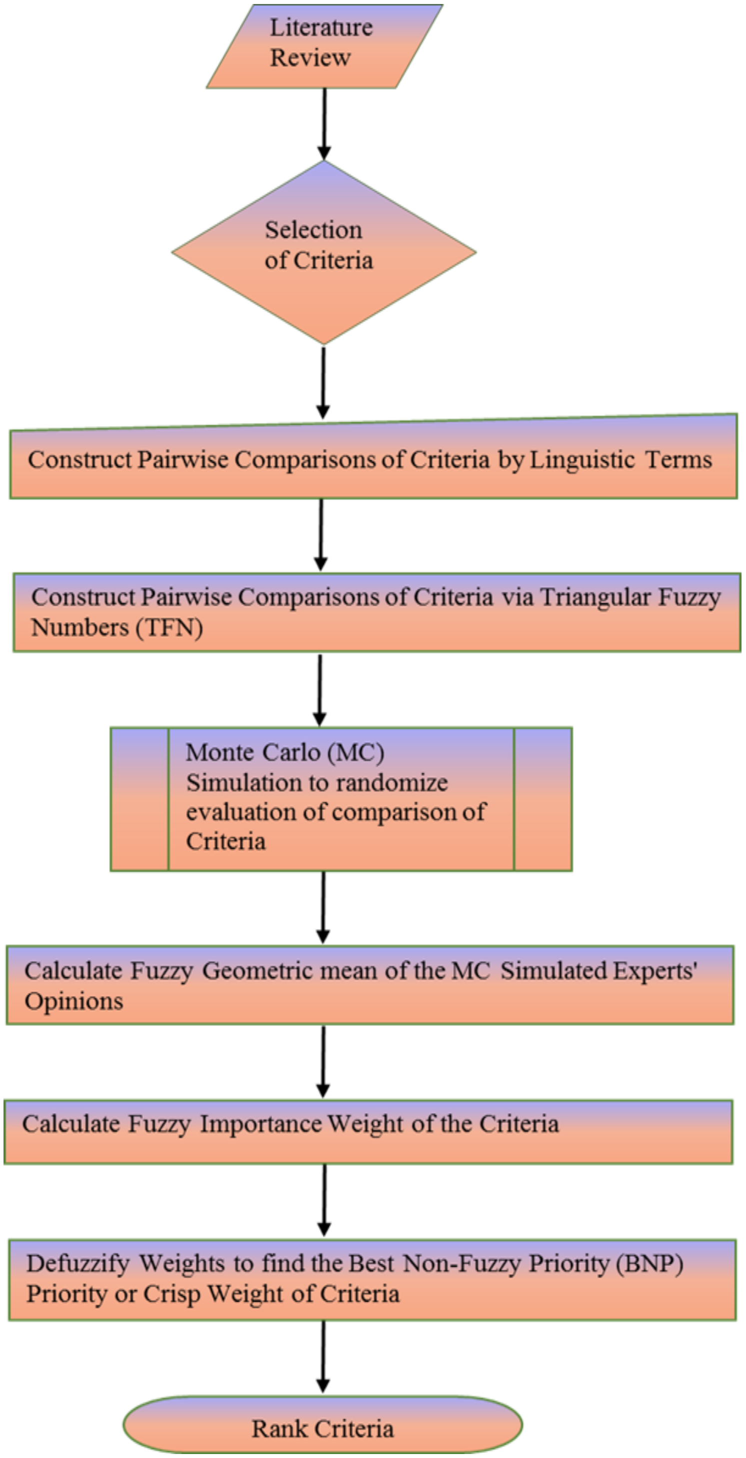


Figure 2. Monte Carlo Simulation in Fuzzy Analytic Hierarchy Process (FAHP)

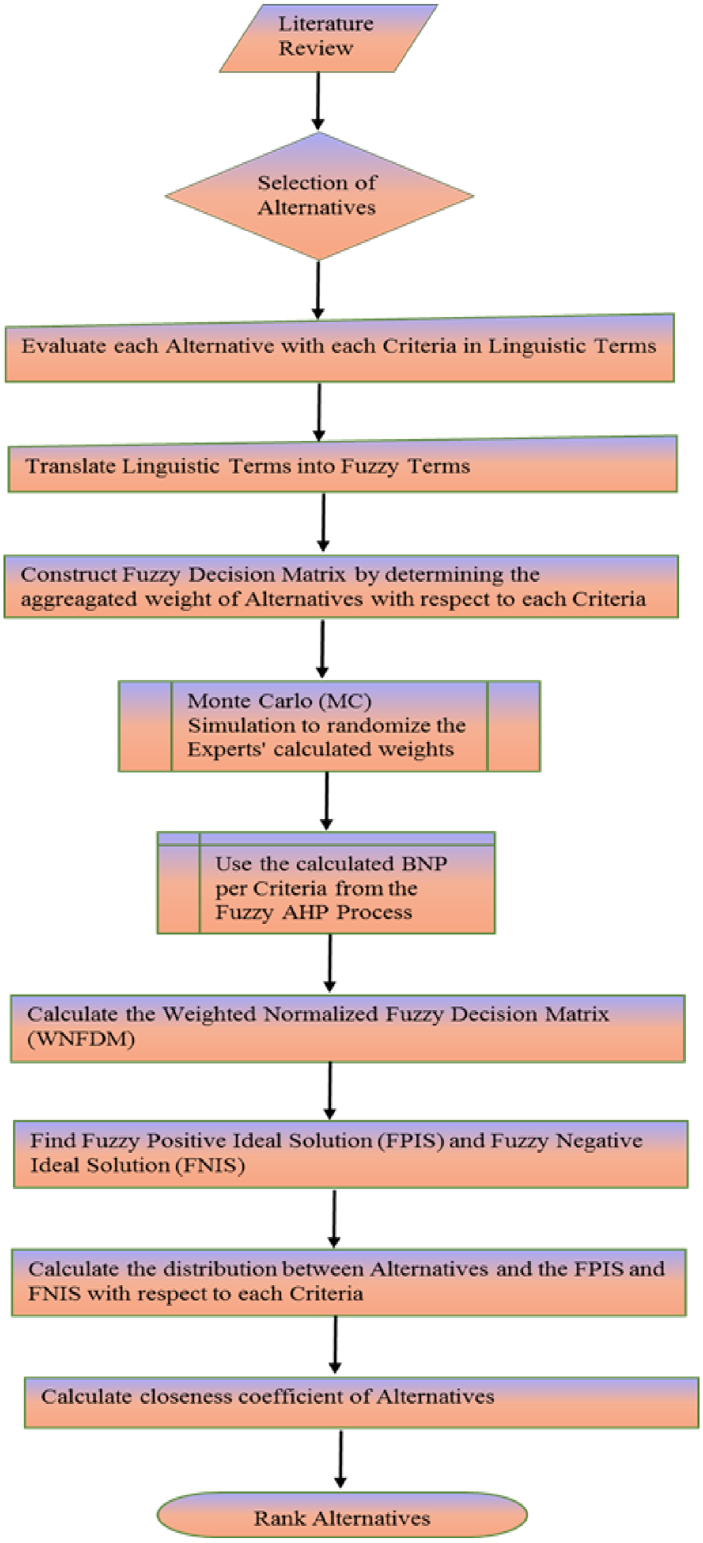
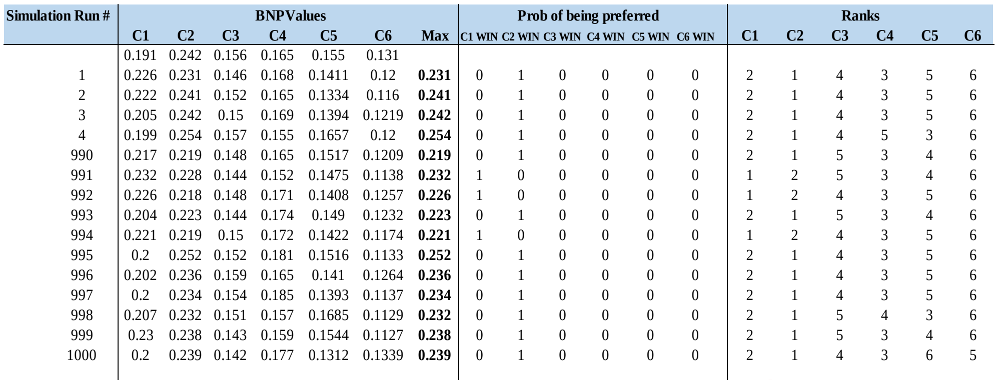


Figure 3. Monte Carlo Simulation in Fuzzy Technique for Order Performance by Similarity to Ideal Solution (FTOPSIS)



Simulation Run #	BNPValues							Prob of being preferred						Ranks					
	C1	C2	C3	C4	C5	C6	Max	C1 WIN	C2 WIN	C3 WIN	C4 WIN	C5 WIN	C6 WIN	C1	C2	C3	C4	C5	C6
	0.191	0.242	0.156	0.165	0.155	0.131													
1	0.226	0.231	0.146	0.168	0.1411	0.12	**0.231**	0	1	0	0	0	0	2	1	4	3	5	6
2	0.222	0.241	0.152	0.165	0.1334	0.116	**0.241**	0	1	0	0	0	0	2	1	4	3	5	6
3	0.205	0.242	0.15	0.169	0.1394	0.1219	**0.242**	0	1	0	0	0	0	2	1	4	3	5	6
4	0.199	0.254	0.157	0.155	0.1657	0.12	**0.254**	0	1	0	0	0	0	2	1	4	5	3	6
990	0.217	0.219	0.148	0.165	0.1517	0.1209	**0.219**	0	1	0	0	0	0	2	1	5	3	4	6
991	0.232	0.228	0.144	0.152	0.1475	0.1138	**0.232**	1	0	0	0	0	0	1	2	5	3	4	6
992	0.226	0.218	0.148	0.171	0.1408	0.1257	**0.226**	1	0	0	0	0	0	1	2	4	3	5	6
993	0.204	0.223	0.144	0.174	0.149	0.1232	**0.223**	0	1	0	0	0	0	2	1	5	3	4	6
994	0.221	0.219	0.15	0.172	0.1422	0.1174	**0.221**	1	0	0	0	0	0	1	2	4	3	5	6
995	0.2	0.252	0.152	0.181	0.1516	0.1133	**0.252**	0	1	0	0	0	0	2	1	4	3	5	6
996	0.202	0.236	0.159	0.165	0.141	0.1264	**0.236**	0	1	0	0	0	0	2	1	4	3	5	6
997	0.2	0.234	0.154	0.185	0.1393	0.1137	**0.234**	0	1	0	0	0	0	2	1	4	3	5	6
998	0.207	0.232	0.151	0.157	0.1685	0.1129	**0.232**	0	1	0	0	0	0	2	1	5	4	3	6
999	0.23	0.238	0.143	0.159	0.1544	0.1127	**0.238**	0	1	0	0	0	0	2	1	5	3	4	6
1000	0.2	0.239	0.142	0.177	0.1312	0.1339	**0.239**	0	1	0	0	0	0	2	1	4	3	6	5

Figure 4. Sample of the Outcome of the MC Simulation in the FAHP Portion of the DMCE Tool

3. DISCUSSION OF RESULTS

A major concern in maritime transportation is the use of formalized procedures to quantify risk and to support decisions associated with significant uncertainty. Elements of MTS are sources of environmental pollution which creates new and critical challenges to port managers. One such challenge is the need to reduce environmental damage while enhancing system performance. Although, multi-criteria decision methods have been implemented to assess these externalities, these methods have limitation in dealing with the imprecise nature of linguistic assessment. Decision-makers face uncertainties from those subjective perceptions and experiences in the decision-making process. To overcome these limitations, fuzzy multi-criteria decision-making methods have been implemented along with an integrated Monte Carlo simulation into this research work in order to expand the awareness of the potential states and outcomes, as well as the probabilities and consequences of outcomes of the alternative decisions. The integration of the MC simulation into the DMCE tool provides a systematic approach to decision-making under uncertainty.

The need to understand how likely the resulting outcomes of criteria and alternative strategies could most significantly enhance the MTS sustainability led to the integration of Monte Carlo simulation into the Fuzzy AHP and Fuzzy TOPSIS DMCE tool. The MC simulation in the FAHP was used to calculate the probabilities of the relative weights of each criteria in Table 2 and then, MC simulation in the FTOPSIS was used to have a better understanding of the probabilities associated with the prioritization of the MTS's sustainable alternatives in Table 3based on the previously selection of criteria.

Four alternative methodologies were ranked to promote sustainability based upon six criteria. As a result, the criteria were evaluated using FAHP with a MC simulation to have a comprehensive understanding of its outcomes. Table 4 depicts the resulting probabilities for each of the criteria under evaluation. The information on Table 4 provides with the percentage of the likelihood of occurrence the criteria to be selected in that ranking position being considered. For example, the likelihood for Criteria 1- Use of green design in ships, engines and machinery, to be ranked in the first position is of 0.095. Moreover, it can be observed that the likelihood of Criteria 1 to be ranked in second position is much greater with a probability of 0.905. This information is valuable to assist in the understanding of the risk in the order of addressing these issues in the maritime industry.

Table 4. Rank Probabilities per Criteria

Evaluation	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**
P(C=R1)	0.095	0.905	0	0	0	0
P(C=R2)	0.905	0.095	0	0	0	0
P(C=R3)	0	0	0.064	0.849	0.087	0
P(C=R4)	0	0	0.56	0.117	0.323	0
P(C=R5)	0	0	0.376	0.033	0.588	0.003
P(C=R6)	0	0	0	0.001	0.002	0.997
Sum	1	1	1	1	1	1

Furthermore, once the criteria weights had been established, it was then possible to evaluate the alternatives using the integrated MC simulation into the FTOPSIS method. Table 5 depicts the resulting probabilities for each of the alternatives under evaluation. The information on Table 5 provides with the percentage of the time or likelihood of the alternative to be selected in that ranking position being considered. For example, the likelihood for Alternative 1- Reduction of release of substances as defined by MARPOL Annex 1-6, to be ranked in the first position is pretty high with a probability of 0.96. Also, it can be observed that the likelihood of Criteria 2 to be ranked in fourth position is high with a probability of 0.94. This information is valuable to assist in the understanding of the risk associated with the order selected to address these issues in the maritime industry. This alternative measures the importance of complying with regulations and policies when trying to increase environmental performance of MTS. The determination of which alternatives have the most influence on the environmental performance of the maritime industry is recorded in their relative ranking. This would allow decision-makers and managers in the industry to develop a plan that improves the sustainable environmental performance of the MTS.

Table 5. Rank Probabilities per Alternative

Evaluation	**A1**	**A2**	**A3**	**A4**
P(A=R1)	0.96	0	0	0.16
P(A=R2)	0.039	0	0.003	0.82
P(A=R3)	0.001	0.069	0.91	0.02
P(A=R4)	0	0.94	0.087	0.005
Sum	1	1	1	1

In order to have a visual understanding on the possible outcomes of these criteria and alternatives being evaluated, Figures 5 and 6 show histograms on the comparison of rank probabilities per criteria and alternatives, respectively. These histograms show possible outcomes of each decision and assess the impact of risk associated with their priority ranking, allowing for better decision-making under uncertainty.

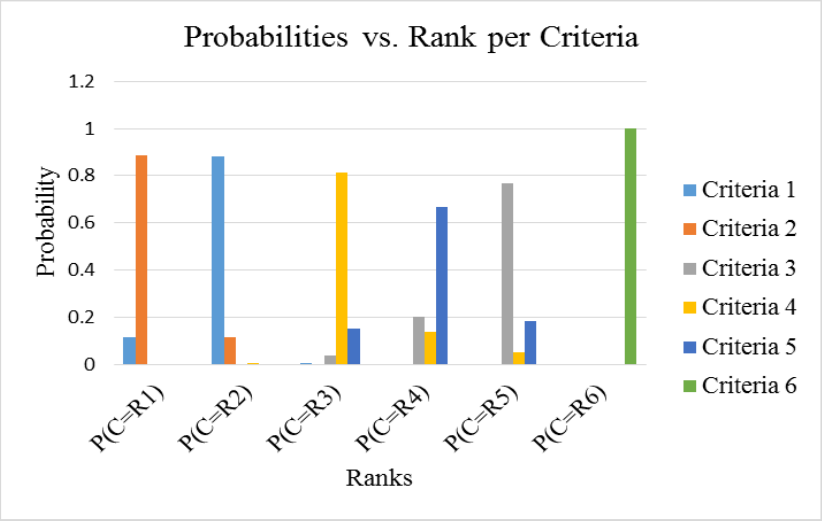


Figure 5. Comparison of Rank Probabilities per Criteria

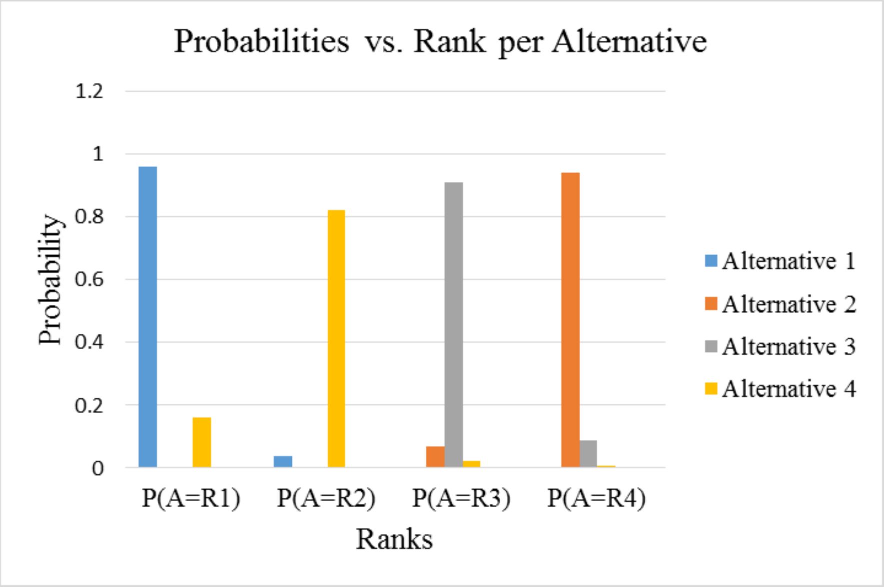


Figure 6. Comparison of Rank Probabilities per Alternative

4. CONCLUSIONS AND FUTURE WORK

This research integrated a Monte Carlo simulation into a Decision Making in Complex Environments (DCME) tool that quantifies and ranks preferred environmental impact indicators within a MTS, in order to add a better understanding to those risks associated with the ranking of these preferred environmental indicators and assists decision makers to achieve goals of improved environmental sustainability. The modified model helps decision makers achieve environmental sustainability and also provide environmental policy-makers in the shipping industry with an analytical tool that can evaluate tradeoffs within the system and identify possible alternatives to mitigate detrimental effects on the environment. The integrated evaluation tool developed in this research can provide marine decision-makers with an analysis of traditional performance evaluation model that includes the uncertainty and imprecision that comes with decision-making in complex environments. The proposed method enables decision analysts in the maritime industry to better understand the complete evaluation process of alternatives and criteria for a sustainable system.

This study fills a gap by evaluating the preferred green performance measures by integrating Monte Carlo methodology into fuzzy logic in the combination of Analytic Hierarchy Process (AHP) and the Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) methods, to measure the key performance indicators of a maritime transportation system with regards to the environment. Consequently, this research developed tool for evaluating the preferred green measures in the MTS. Moreover, the tool helps add a more comprehensive understanding that uncertainty associated to risk that reduces the MTS's performance, and attempts to get a better understanding on the beneficial elements and performance measures that positively impact the system's environmental performance.

For future work, we propose to expand the model and evaluate the alternatives with respect to more detailed criteria. Also, since results of this research are based on the criteria and alternatives identified through examination and surveying of related literature through maritime experts, the testing and validation of the tool is limited to the experiences and knowledge of those chosen as experts. The incorporation of a greater number of experts could yield more accurate results with respect to the distributions for the Monte Carlo simulation and hence, have a better understanding of the behavior of the preferred green performance measures in the maritime industry to attain an environmentally sustainable system.

Moreover, the comprehensive methodology developed in this research can be implemented to evaluate other systems and infrastructures. This will allow decision makers to identify those preferred performance indicators in order to make strategic decisions and enhance the efficient and environmental performance of the maritime system.

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IV. REMOTE SENSING ANALYSIS AND MATHEMATICAL MODELING FOR VEGETATION MONITORING OF NEAR-PORT AREAS

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ABSTRACT

Maritime Transportation Systems (MTS) are responsible for approximately 90 percent of global trade. Although shipping is considered a more efficient and eco-friendly means of transporting large quantities of freight over significant distances at low costs, it can put significant pressures on port capacity and the natural environment. Maritime shipping is responsible for 2.2 percent of the world's greenhouse gas emissions during 2012 according to the International Maritime Organization. It also can impact the local and regional environment around a port facility due to atmospheric, water, soil and noise pollution. As maritime shipping activity increases in existing port facilities, procedures to enhance environmental sustainability become an even more pressing concern. The impact of MTS may be more significant at local and regional levels near port facilities. This work looks at one of the challenges of determining and being able to attribute the impact that maritime activity has towards vegetation near-port areas; the overwhelming volume of data. Therefore, in this work remote sensing using satellite images of the Port of Prince Rupert, British Columbia, Canada area were utilized to determine the environmental impact maritime activity has had over the vegetation near the port over the last 32 years. Data analytics was a vital component in the understanding of the long-term environmental impact that MTS has towards the environment. A multi-variate regression analysis was implemented to evaluate external variables or reasons, such as meteorological data, for the building of a model that explains the vegetation index behavior. This resulted in a model for vegetation monitoring of near port areas. The developed models can help decision-makers evaluate the direct impact that maritime activity has towards the environment and help improve the performance of the system with regards to the environment.

KEYWORDS

Sustainability, Maritime Transportation System, Satellite Imagery, Remote Sensing, Time Series Analysis, Multi-variate Regression Analysis

1. INTRODUCTION

Maritime Transportation System (MTS) is a vital component of transportation systems. Approximately 90 per cent of world trade by volume and over 70 per cent by value are transported on vessels and handled at ports all over the world (UNCTAD, 2015). Although shipping is considered environmentally efficient in comparison to the other major modes of transportation, it is a non-negligible source of atmospheric emissions. MTS is estimated to be responsible for 2.2 per cent of the world's greenhouse gas emissions during 2012 (IMO, World Maritime Day: A Concept of a Sustainable Maritime Transportation System, 2015). Also, 1.9 per cent of the global emissions of CO_2 in 2012 are attributed to MTS and CO_2 emissions from MTS are forecasted to increase significantly due to expected growth in global trade arising from globalization (IEA, 2014).

Maritime transportation is indispensable as a mode of mass transport in the future global economy. Therefore, in order to cope with the environmental impacts, the maritime transportation industry is receiving pressure from its customers and stakeholders to emphasize on proactive environmental managerial strategies. By understanding and identifying the types of environmental impacts emanating from transportation operations and activities and pinpointing the interactions amongst maritime transportation activities that have negative environmental impacts, MTS can better measure sustainable performance metrics.

As stated previously, maritime transport is indispensable in a sustainable future global economy as it is the most environmentally rigorous of mass transport, both in terms of energy efficiency and the prevention of pollution. Although environmental, social and economic dimensions of maritime transport are equally important and should be fully recognized in any strategy, policy, regulatory framework or action, this research focuses on environmental impacts over time.

There is this perception that shipping is a minor contributor to air pollution, because of its efficiency. However, because shipping accounts for a significant annual tonnage and transported over large distances, it results in substantial global emissions. It is recognized that port activities pose adverse regional impacts on air, water, soil and sediments (Dinwoodie et al., 2012). Around 95 percent of fuels used in the maritime transport sector are fossil based. By transport depending heavily on oil propulsion, this sector emits large amounts of greenhouse gases (GHGs), notably carbon dioxide (CO_2) and other air emissions such as nitrogen oxides (NO_x), sulphur oxides (SO_x), volatile organic compounds, particulate matter and lead. Also, it has been calculated that 3.5 to 4 percent of all climate change emissions are caused by shipping (Vidal, 2009). Also, of the total global air emissions, shipping accounts for 18 to 30 percent of the nitrogen oxide (NO_x) and 9 percent of the sulphur oxides (SO_x) (Schooten, et al., 2009). All these emissions have negative impacts towards the environment and the climate.

An important challenge faced in the shipping industry is how to support and attribute positive change to evolving technologies and procedures, when the current damage from marine activities is not completely understood. Hence, the focus of this research is on the study and understanding of the environmental impact of the maritime activity. The study area is the Port of Prince Rupert, British Columbia, Canada and surrounding areas over the past 32 years. Satellite images are analyzed to measure the environmental impact of maritime activity on the vegetation near the port. This enables the modeling of the environmental impact over time by on-going maritime transportation activity and to identify alternate means of controlling and preventing environmental pollution and natural resource degradation from activities related to maritime transportation.

1.1 PORT OF PRINCE RUPERT, BRITISH COLUMBIA, CANADA

The Port of Prince Rupert (PPR) is North America’s closest port to Asia by up to three days sailing – it’s 36 hours closer to Shanghai than Vancouver and over 68 hours closer than Los Angeles, making it the fastest route in the transpacific (The Port of Prince Rupert, 2016). Also, the PPR has superior and uncongested rail connection into North American markets through Canadian National Railway’s (CNR) 'coast-to-coast-to-coast' rail network, providing efficient and consistent access to key customers throughout Canada and the United States (The Port of Prince Rupert, 2016). The port of Prince Rupert has a terminal capacity of 850,000 twenty-foot equivalent unit TEUs annually and is currently undergoing expansion (The Port of Prince Rupert, 2016). But it is the relative isolation of Prince Rupert as a maritime transport hub, well removed from other inhabited communities, that makes it ideal for environmental impact research. The Port of Prince Rupert is located in western Canada in British Columbia, at a latitude of 54.3150° North with longitude of 130.3206° West, and is surrounded by mountains and plenty of vegetation. Figure 1 depicts the vegetation surrounding the PPR in a Landsat satellite image at 1:50,000 scale (Landsat, 2017). As observed in the satellite image, the surrounding areas of the PPR, enclosed in a yellow line, do not present a population density as congested as other major container ports. Also, the Port of Prince Rupert has only been in operation as an intermodal containerized port since 2007. These last facts, its location and years in operations, make this port a grand asset for our study.

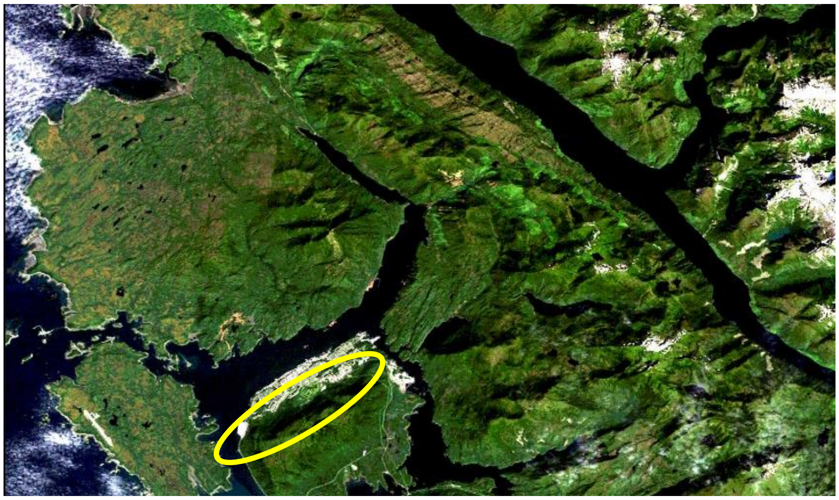


Figure1. Satellite Image of the Port of Prince Rupert
http://landsatlook.usgs.gov/viewer.html

As container traffic increases, ports continue to increase in size and throughput in order to compete in global trade. Ideally, this growth should take place without imposing additional externalities that harm the environment (Melious, 2008). Hence it is essential for ports to adapt to twenty-first century concerns and implement best practices to reduce their environmental impacts at both local and global levels.

As previously mentioned and depicted in Figure 1, the port at Prince Rupert, British Columbia is a container port located in a small town away from population centers and would appear to be less constrained by the environmental concerns that dominate and affect the West Coast port competitors (Melious, 2008). The PPR has contributed to the major local impacts of port operation: air pollution and invasive species transport in ballast water. But from the time when it became and international containerized port in 2007, its local impacts are relatively new and not completely understood.

Studies making use of geographic marine activity data have estimated that about 70–80 percent of all ship emissions occur within 400 km (248 miles) of land (IMO, 2000 and Corbett et al., 1999). Therefore, these pollution problems are a concern about the impact that ports have towards the environment (Melious, 2008). An inaccurate perception on the consequential port environmental problems results in a competitive disadvantage towards those ports that are more careful about their effect towards the environment. Consequently, making ports environmental-friendly and having greener credentials results in competitive advantages including the attraction of business.

1.2 PURPOSE OF STUDY

This research focuses in the understanding of the environmental impact of the maritime activity at the Port of Prince Rupert (PPR), British Columbia, Canada to surrounding areas along the years. In this research, the need for predictive tools that are accurate and robust in order to understand the impacts maritime activity at the PPR have towards near-port vegetation and consequently assist with effective environmental decision-making, addressed. Fairview Container Terminal was the subject of an environmental screening under the Canadian Environmental Assessment Act (CEAA) in order to determine environmental issues. The terminal's environmental screening limited the negative effect of the terminal's impact towards the environment to the on-going expansion instead of the harming its on-going activity could be having towards the environment at local or global levels. The air quality analysis did not calculate projected air emissions given the existing conditions and also, no effort was made to identify or quantify the air pollutants, such as SOx, NO_x, and diesel particulates. Instead, the analysis stated that due to the no notifiable harming caused by past emissions, it was not expected for the Fairview Terminal to have a negative effect on air quality or surrounding areas near the port in the near future (CEAA, 1992). In this research, satellite images will be analyzed to understand and collect vegetation data to numerically evaluate the environmental impact of the port. This enables the modeling of the on-going maritime transportation system activity and the environmental impact the system is expected to have over time over the near-by areas, and therefore identifying alternate means of controlling and preventing environmental pollution and natural resource degradation from activities related to maritime transportation along the years.

2. METHOD

Environmental management and monitoring in an era of global change can be quite complex and the consequences of decisions can often be highly uncertain (Polasky et al., 2011). Scientific findings specify that changes to the global environment are occurring at an exceptional rate, affecting plants and animals, and the quality of human lives as well (Thomas & Roller, 1993). The environment is considered multi-dimensional, multi-functional, highly complex and dynamic therefore, this rather complex real-world problem is a challenge for the development of systems thinking approaches that explain, explore, and predict the environment's behavior in order to ensure proper mitigation strategies (Klug and Kmoch, 2015). Modelling and monitoring efforts are considered key for sustainable environmental planning (Jorgensen, Refsgaard, & Hojberg, 2007). In order to make reliable models that best guide decision-making towards sustainability and meet present and future needs, an enhanced ability to gather and analyze existing information is required.

A sustainable Maritime Transportation System (MTS) requires coordination at local and global levels. The coordination for environmental protection must take into account sustainable development by promoting safety by adhering to the best practices in the industry based to global standards and applying them, maximizing energy efficiency and resource conservation, and minimizing pollution, while enabling seamless and reliable maritime transport around the world (IMO, 2015). Preference has been given to the acquiring of data on vegetation cover changes over periods of time in order to better assess the environment and the surrounding ecosystems (Knight et. al, 2006). In this research the Normalized Difference Vegetation Index (NDVI) and the Thiam's Transformed Vegetation Index (TTVI) are calculated from the Landsat imagery then, a multi-variate regression analysis is applied in order to develop a model that evaluates the environmental impact of maritime activity in the vegetation near the port activities. This will help with the understanding of the environmental impacts of shipping and assist with the protection of the environment by ensuring sustainability of the MTS.

2.1 REMOTE SENSING

Assessing and monitoring the state of the earth surface is a key requirement for global change research (Jung *et al.* 2006; Lambin *et al.* 2001). Land surfaces (including vegetation) possess unique spectral features (reflectance or emission regions), they can be identified using remote sensing imagery due to their unique spectral characteristics. An example in vegetation mapping by using remote sensing technology is the spectral radiances in the red and near-infrared regions, among others.

One of the main applications of remote sensing in environmental studies and analysis and environmental management decision-making is the detection and quantitative assessment of green vegetation (Silleos et al., 2006). The classifying and mapping of vegetation allows managing and analyzing natural resources, such as the influencing CO_2 in the vegetation (Xiao *et al.* 2004). Traditional methods (e.g. field surveys, literature reviews, map interpretation and collateral and ancillary data analysis), are not as effective in acquiring vegetation information because they are time consuming, date lagged and often too expensive due to the hours of man power. The technology of remote sensing offers a practical and economical means to study vegetation cover changes, especially over large areas (Langley *et al.* 2001; Nordberg and Evertson, 2003). Moreover, remote sensing technology has the potential to extend possible data archives from present time back through several decades allowing for a better collection of data and a more comprehensive study.

Remote sensing is an efficient technique for vegetation analyses and detection and monitoring of changes in vegetation patterns. When the area of vegetation under study is healthy green, it has a very distinct interaction with certain portions of the electromagnetic spectrum. In the visible regions, chlorophyll causes a strong absorption of energy, primarily used for photosynthesis. This strong absorption of energy results in peaks in the red and blue areas of the visible spectrum, while the green area is reflected by chlorophyll hence, leading to the green appearance leaves. Simultaneously, the near-infrared region of the spectrum is strongly reflected through the internal structure of the leaves. It is in fact due to this strong contrast, the reflected energy in the red and near-infrared regions of the electromagnetic spectrum, what has caused the incentive to develop quantitative indices of vegetation condition using remotely sensed imagery (Silleos et. al, 2006).

2.2 NDVI AND TTVI

Vegetation extraction from remote sensing satellite images is based on the analysis of the image's color, texture, tone, pattern and association information, etc. Diverse methods have been developed to do this.

The Normalized Difference Vegetation Index (NDVI) is the most commonly used index of plant "greenness" or photosynthetic activity (Rouse et al., 1974). Vegetation indices are based on the observation that different surfaces reflect different types of light. Photosynthetically active vegetation tends to absorb most of the red light that hits its surface while reflecting much of the near infrared light. Vegetation that is dead or stressed tends to reflect more red light and less near infrared light. Likewise, non-vegetated surfaces have a much more even reflectance across the light spectrum.

By taking the ratio of red and near infrared bands from a remotely-sensed image, an index of vegetation "greenness" can be defined as expressed in Equation 1 (Silleos et al., 2006). NDVI is calculated on a per-pixel basis as the normalized difference between the red and near infrared bands from an image:

$$\text{Normalized Difference Vegetation Index (NDVI)} = \frac{Red - NIR}{Red + NIR} \qquad (1)$$

The output values of NDVI can range from -1.0 to +1.0, but values less than zero have no ecological meaning, so the range of the NDVI is usually truncated to 0.0 - +1.0. Higher values signify larger difference between the red and near infrared radiation recorded by the sensor - a condition associated with highly photosynthetically-active vegetation. Low NDVI values mean there is little difference between the red and NIR signals. This happens when there is little photosynthetic activity, or when there is just very little NIR light reflectance.

Because of its ease of use, NDVI has seen widespread use in rangeland ecosystems' analysis. The uses include assessing or monitoring: the vegetation dynamics or plant changes over time, the soil moisture and/or the carbon sequestration or CO_2 flux (Tool, 2016).

Another commonly used vegetation index is Thiam's Transformed Vegetation Index (TTVI), which creates a vegetation index that describes the greenness and health of vegetation for each picture element or pixel in a satellite image.

TTVI was first suggested by Richardson and Wiegand (1977), and it's a modification to the NDVI (Equation 2) (Silleos et al., 2006).

$$\text{Thiam's Transformed Vegetation Index (TTVI)} = \sqrt{ABS(NDVI + 0.5)} \qquad (2)$$

Moreover, the calculation of the square root was added with the intention of correcting the NDVI values that approximate a Poisson distribution and henceforth introduce a Normal distribution. In terms of the image output or active vegetation detection, no technical difference exists between the two vegetation indexes.

In this research, satellite images of the Port of Prince Rupert area were collected for the years 1984-2015. The bands collected for these images were the Red and the Infrared bands. QGIS Software, (previously known as "Quantum GIS"), a cross-platform free and open-source desktop geographic information system (GIS) application that provides data viewing, editing, and analysis, was utilized to extract data from the collected red and infrared bands for the area of the PPR (QGIS, 2017). QGIS allowed for a composite of raster or vector layers to be built (Figure 2) using the NDVI and TTVI vegetation indexes.

After creating the raster layers by utilizing the NDVI and TTVI equations to create a layer that resulted in the output of the equations, QGIS software was utilized to run a raster layer statistics for each of the raster's created for each year, in order to attain the mean values for the vegetation indexes.

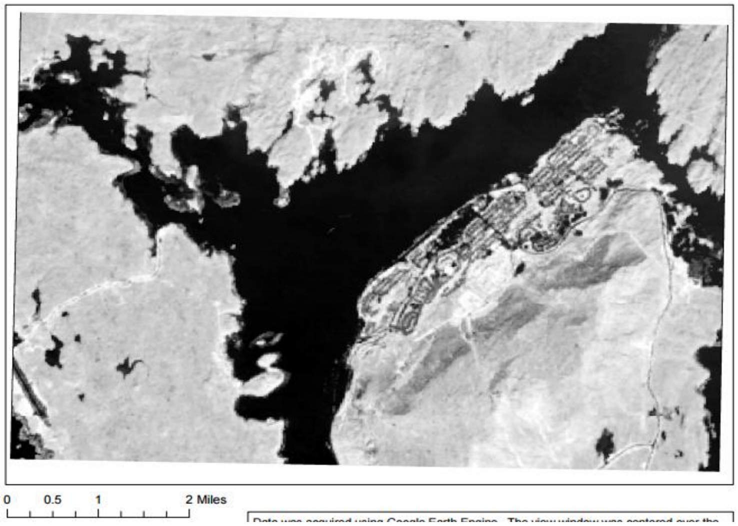


Figure 2. Satellite Image of the Area under Study Surrounding the Port of Prince Rupert processed in QGIS Software to attain mean values of NDVI and TTVI

After calculating the mean values for the vegetation indexes for 32 years in the area around PPR, a time series of the mean NDVI can be created (Figure 3). Figure 3 shows through a least-squares regression that there is a trend of progressive greening of the surrounding area during this time period. This is counter to what was expected, especially since the expansion of the port since 2007 into an intermodal containerized port with increasing throughputs and more congestion. In Figure 3 the mean NDVI values can be observed along with the t-based 95% confidence intervals (CI) for the mean. It can be observed that only the mean NDVI for the year 2005 was an outlier, which can be explained by the deforestation that took place near the port area due to the expansion to be become and international containerized port in 2007. Mean NDVI values for the years 1989, 2000, 2001, 2002 and 2012, were excluded from the analysis given that during those years errors on the data were found due to satellite malfunctions or noisiness in the satellite images. As observed, the time series for vegetation yielded a positive trend for vegetation but a more robust analysis to explain this positive trend needs to take place. For that external variables that tend to impact the vegetation near the port were considered in order to build a better predictor model for the behavior of vegetation near the PPR. Discussion on the external variables and the model built takes place in the Multi-Variate Regression Analysis section below.

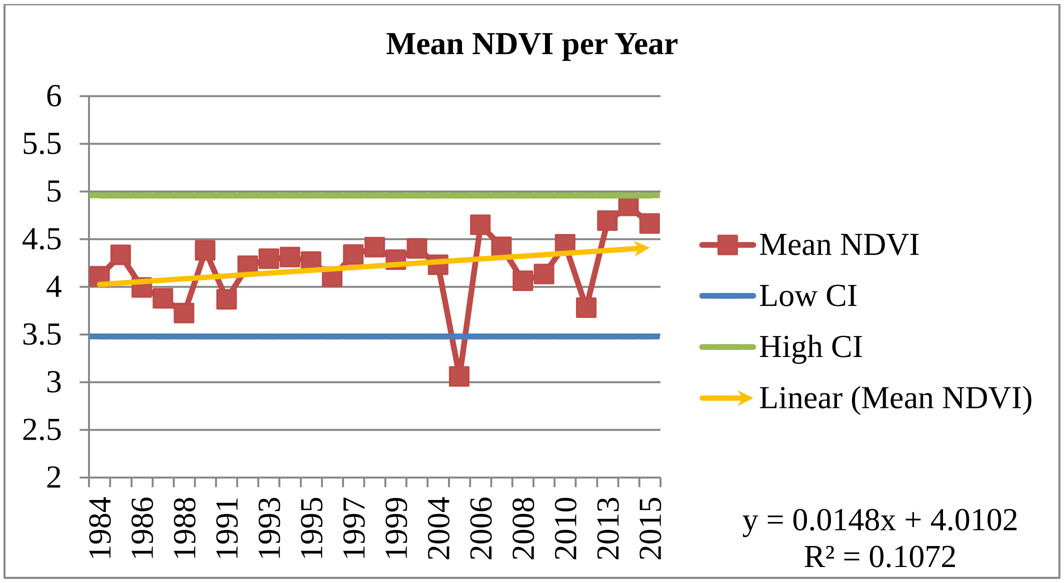


Figure 3. Mean NDVI from years 1984 through 2015

2.3 MULTI-VARIATE REGRESSION ANALYSIS

To understand the behavior of the TTVI as a function of time, an extensive search for external parameters that could influence this behavior took place. The specific question addressed in this research is the following:

How the dependent variable of Vegetation Index gathered from the satellite images of the Prince Rupert, BC area is affected by the following independent variables explained in Table 1.

These data would be utilized to build a multi-variate regression model to explain some of the root causes for the TTVI in the area around PPR exhibit the greening seen in the time series.

Table 1. Variables for the Multi-Variate Regression Analysis

Variables	Unit
Normalized Thiam's Vegetation Index	Unitless
Population of Prince Rupuert, BC	Million
Throughput of PPR	Tons/Year
Total GHG Emissions	Tons of CO2 eq
Total CO2 Emissions	Tons of CO2 eq
Total CH4 Emissions	Tons of CO2 eq
Total N2O Emissions	Tons of CO2 eq
Total HFCs Emissions	Tons of CO2 eq
Total PFCs Emissions	Tons of CO2 eq
Total SF6 Emissions	Tons of CO2 eq
Fine Particulate Matter	µg per cubic m
Sulfur Dioxide Concentration (SO2 avg)	ppb
Ozone Concentration	ppb
Nitrogen Dioxide Concentration (N2O avg)	ppb
Volatile Organic Compound Concentration	ppb of Carbon

Data gathered on the different parameters evaluated in the model is presented in Table 2. The data for the population of Prince Rupert was gathered from the British Columbia governmental website (British Columbia, 2017). The data for the total throughput of the PPR was collected from the Prince Rupert Port Authority main website (PRPA, 2017). The data for the total emissions of GHG, CO_2, CH_4, N_2O, HFCs, PFCs and SF_6 were gathered from the Government of Canada's main website on *Emissions Data* (Government of Canada, 2017). And the data on the concentrations over the British Columbia region on PM, SO_2, Ozone (O), NO_2, and Volatile Organic compound (VO) were collected from Government of Canada main website on *Environment and Climate Change Canada*: *Air Indicators* (Government of Canada, 2017). As observed, due to lack of data availability, some of the parameters are at a local level while others are on a greater scale to the whole Canada level.

Table 2. Data for Multi-Variate Regression Analysis

Data for Multi-Variate Regression Analysis

Mean TTVI	**Year**	**Population (M)**	**Total Tonnage Handled**	**Total GHG**	**Total CO2**	**Total CH4**	**Total N2O**	**Total HFCs**	**Total PFCs**	**Total SF6**	**PM avg**	**SO2 avg**	**O Concentration**	**NO2 avg**	**VO avg**
0.831	2004	4155017	4197272	278385637	258574910	8314358	6002916	27103	3503567	1962784	7.1	25.7	27	1.8	13.7
0.804	2005	4195764	4230843	277996615	258036532	9612518	5662431	58924	3545983	1080228	6.5	19.5	25.7	1.8	13.6
0.678	2006	4241691	7619500	271940210	253852755	9672291	4147659	45112	3033998	1188395	5.8	17.1	24.9	1.5	13
0.738	2007	4290988	10464800	277271363	260475605	9604358	4174483	22823	2665617	328477	5.8	18	28.3	2.1	13.2
0.759	2008	4349412	9871200	263309360	246637535	9210270	4689225	18102	2588983	165245	5.2	17	25.3	1.8	12.1
0.775	2009	4410679	11255700	253008322	235178034	11828182	3096341	308582	2468900	128282	5.3	16.4	26.5	2.1	11.9
0.85	2010	4465924	14994200	263495520	246382902	11815970	2751660	629352	1797753	117885	5.8	18.5	27.5	2.2	12
0.771	2011	4499139	18780400	255586572	238524580	11939507	2621044	649587	1774181	77674	6.6	34.7	27.3	1.8	10.2
0.684	2013	4582607	5364392.5	259287439	241733434	12649056	2439741	568295	1796952	99961	5.2	14.8	27.5	1.6	9.9
0.684	2014	4638415	6181180	260741913	242396766	13951962	2308022	441480	1467920	175763	5.4	17.8	28.7	1.7	10.3
0.672	2015	4683139	7764118	263935802	247740948	12247857	2387168	445673	1073838	40318	6	16.2	25.9	1.6	10.3

3. DISCUSSION OF RESULTS

Multiple linear regression models a *linear* relationship between one quantitative response variable (Y) and several explanatory variables (X). The statement of the model is as follows (Kutner et al., 2004):

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \cdots + \beta_{p-1} X_{i,p-1} + \varepsilon_i$$

Where,

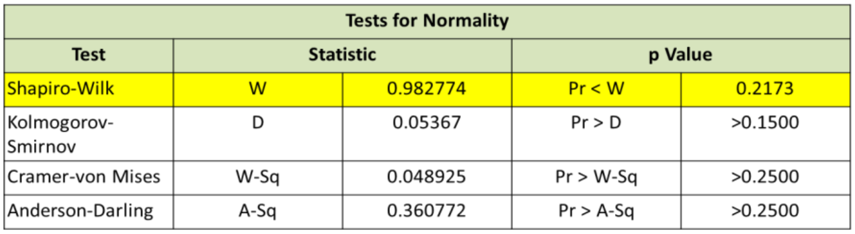
- There are $i = 1, \ldots, n$ observations
- There are $p - 1$ explanatory variables (predictors), and
- There are p regression coefficients (parameters)
- Also, the assumptions are exactly as before: $\varepsilon_i \overset{iid}{\sim} N(0, \sigma^2)$
- Y_i is the value of the response variable in the ith case
- X_{ik} is the value of the kth explanatory variable for the ith case
- β_0 is the intercept, or the value of the response when all explanatory variables are zero, and
- $\beta_{1,}\, \beta_2, \ldots, \beta_{p-1}$ are regression coefficients (slope) for the explanatory variables

A way of analyzing the parameters is that it is expected that a unit increase (or decrease) in explanatory variable X_1 to result in a β_1 increase (or decrease) in the mean response, after holding all the other variables constant. Parameters as usual include all the $\beta's$ as well as σ^2, and these need to be estimated from the data in order to analyze them.

The term *linear*, refers to the parameters, not the explanatory variables. Therefore, *linear* regression can be used to deal with almost any "function" of a predictor variable. For example, functions such as: X^2 and log(X) can be explained using *linear* regression models.

To start analyzing the data, a series of tests were performed. Among them the normality testwere results showed that the data follows a Normal distribution. SAS Statistical Software was utilized to perform the analysis, and SAS provides four different statistics for testing normality. Since the number of observations is less than 2,000, we took look at the Shapiro-Wilk W statistic 0.982774 and its p value 0.2789, presented in Table 3. They provide solid evidences not to reject the null hypothesis that the variable is normally distributed. Although the rest three statistics do not reject the null hypothesis, it is not relevant to interpret them due to the sample size used in this analysis. Therefore, the null hypothesis states that the data follow a normal distribution. Because the p-value is 0.2173, which is greater than the significance level of 0.05, the decision is to fail to reject the null hypothesis. You cannot conclude that the data do not follow a normal distribution.

Table 3. Normality Test Results for Sample Data



Tests for Normality				
Test	**Statistic**		**p Value**	
Shapiro-Wilk	W	0.982774	Pr < W	0.2173
Kolmogorov-Smirnov	D	0.05367	Pr > D	>0.1500
Cramer-von Mises	W-Sq	0.048925	Pr > W-Sq	>0.2500
Anderson-Darling	A-Sq	0.360772	Pr > A-Sq	>0.2500

Followed a model refinement and selection which helped running all possible combinations of models and use different model selection criteria to make the "best" model decision. The following statistics were used for the model selection:

a. R^2 and SSE (ex. it desired a high R^2 value which will reflect a low SSE)

b. Adjusted R^2 and MSE

c. AIC (Akaike's Information Criterion) and BIC (Schwarz's Bayesian Information Criterion)

d. Mallow's C_p Criterion

e. PRESS Statistic

And the techniques for model selection utilized were:

a. "Best" Subsets Algorithm

a. Forward Selection

b. Backward Elimination

c. Stepwise Selection

d. Sequential Replacement

Ultimately, the "best" model to be selected is depicted in the *Summary of Model Selection* shown in Table 4. As observed in the results presented in Table 4, the "best" model to explain vegetation changes near the PPR includes a total of 8 variables: total tonnage, total N_2O (Nitrogen dioxide), the average concentration of PM (Particulate Matter), total CO_2 (Carbon dioxide), the average concentration of N_2O (Nitrogen dioxide), total SF_6 (Sulfur hexafluoride), total GHG (greenhouse gas emissions), and total CH_4 (Methane).

The multi-variate model to explain the vegetation changes near the Port of Prince Rupert, British Columbia, Canada is presented in Table 5 were the model parameters are shown. This model presented in Table 5 is the "best" model to explain the relationship between the mean TTVI surface reflectance index attained using the remote sensing technique from the vegetation near the PPR, and the external variables (parameters) found significant to impact the vegetation. As presented in Table 4, the model selected yields a R-Square value of 0.969, which results on that 96.9 percent of the variation on the mean TTVI can be explained by the parameters selected in the multi-variate regression model.

Table 4. Summary of “Best” Model Selection for Vegetation Monitoring

Summary of Model Selection					
Step	**Variable Entered**	**Variable Removed**	**# Vars In**	**Partial R-Square**	**Model R-Square**
1	Ttonnage		1	0.264	0.264
2	THFs		2	0.314	0.578
3	TN2O		3	0.097	0.676
4	PMavg		4	0.096	0.771
5	SO2avg		5	0.068	0.839
6	TCO2		6	0.032	0.871
7	NO2avg		7	0.019	0.89
8		THFs	6	0.003	0.887
9	TSF6		7	0.039	0.927
10	TGHG		8	0.02	0.946
11	TCH4		9	0.023	0.969
12		SO2avg	8	0.002	0.966

Table 5. Multi-Variate Model Parameters

Variable	Parameter Estimate
Intercept	3.83441
Ttonnage	-0.00000111
TGHG	4.09E-07
TCO2	-4.07E-07
TCH4	-3.36E-07
TN2O	-2.34E-07
TSF6	-6.20E-07
PMavg	-4.72E-07
NO2avg	0.18236

4. CONCLUSIONS AND FUTURE WORK

In this research, the technology of remote sensing was utilized by gathering and analyzing satellite images of the Port of Prince Rupert, BC, Ca area to extract vegetation index data and determine the environmental impact maritime activity has had over the vegetation of near port areas over the last 32 years. After extracting data and understanding the behavior of vegetation changes, this research proceeded to develop a multi-variate regression model to evaluate the most relevant factors related to maritime activity that affect the vegetation index. This would aid in the vegetation monitoring over the years and to explain how maritime activity affects near port areas.

The developed model helps explain the direct impact maritime activity has towards the near-port environment. Results from the multi-variate regression analysis showed those variables found to be significant in the vegetation changes near the PPR over the years. This analysis led to a prediction model for the vegetation monitoring on near port areas.

There is no question that maritime transportation is an essential component of globalization for sustainable development because the world relies on a safe, secure and efficient international shipping industry. This can only be achieved under the comprehensive regulatory framework for countries to develop their maritime transport infrastructure in a safe, efficient and environmentally sound manner. By understanding the impact maritime activity has on the environmental along the years, one could develop a framework for the sustainable development of maritime activities using the environmental key performance indicators in a more accurate manner.

A Sustainable Maritime Transportation System requires coordinated support from the shore-side entities intrinsic to shipping. By developing a model that looks at environmental impact indicators and their drivers to analyze how the Port of Prince Rupert in Canada has impacted surrounding areas throughout British Columbia and what their long-term impact might be with current environmental policies, an evaluation and assessment could take place to understand and measure the MTS’s sustainable performance. Future work will include the results attained in this paper of those significant variables found to have an impact on the vegetation near the port, along with variables that measure the operational performance of the MTS in order to build a Multi-Objective Optimization model that will evaluate the performance of the system with regards to the environment.

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SECTION

2. CONCLUSIONS OF DISSERTATION AND FUTURE WORK

This chapter reviews the main research contributions discussed in this dissertation, overviews the conclusions, and discussed potential future work. The main objective of this dissertation was to develop with analytical tools to address problems in the shipping industry associated with environmental hazard identification, assessment and control for a sustainable Maritime Transportation System (MTS). These analytical tools assist decision-makers and environmental policy makers in determing optimal paths to achieve sustainability, system effectiveness, efficiency, and environmental impact mitigation from MTS activity.

The first research contribution outlined how a systems thinking approach could be utilized to to develop a system dynamics simulation model to study the Port of San Juan under the disruptive impact of a natural disaster such as Hurricane Georges (1998). With this model it could be observed the impact that the disaster's damage would have on different elements taking part in the MTS. By understanding how the different components of the system behave when impacted by a disaster, their relationships and behavior could be studied allowing the necessary steps to ameliorate performance and reduce the negative impact to be determined. This research detailed model development and outlined steps for using real-world information to better assist maritime port managers with disaster planning and recommend best practices to mitigate storm damage.

The second research contribution, developed a decision making in complex environments (DMCE) tool by integrating the methods of fuzzy Analytic Hierarchy Process (AHP) and the fuzzy Technique for Order Performance by Similarity Ideal Solution (TOPSIS). By applying fuzzy logic into these decision-making methods, an evaluation of the preferred performance indicators with regards to the environment took place in order to achieve environmental sustainability in the maritime transportation system. The developed DMCE tool can be implemented for the understanding of the preferred criteria and alternatives of numerous complex systems.

In third research contribution, a Monte Carlo simulation was added to the DMCE tool developed as research contribution 1, in order to quantify the risk of each criteria and alternative preferred for an environmentally-sustainable system. This allows the tool to yield the probabilities and risks associated with the ranking of each of the criteria and alternatives evaluated and consequently, provide marine decision-makers with an analysis of a performance evaluation model that includes the uncertainty and imprecision that comes with decision-making in complex environments.

The fourth research contribution consisted of applied remote sensing by gathering and analyzing satellite images of the Port of Prince Rupert, BC, Canada area to extract vegetation index data and determine the environmental impact maritime activity has had over the vegetation of near port areas over the last 32 years. This data extraction was used to develop a model for vegetation monitoring to explain how maritime activity affects near port areas. Also, by considering external variables such as temperature, precipitation, emissions and throughput tonnage of the PPR, a multi-variate regression model to evaluate the most relevant factors related to maritime activity that affect the vegetation index was developed. This model helps explain the direct impact maritime activity has towards environment near the port.

Future work will involve the development of a multi-objective optimization model for a sustainable maritime transportation system. Environmental performance indicators, the environmental impacts of maritime activity towards the environment, and regulatory policies will be used as criteria and decisive variables on the MTS planning and management model. The model will be constructed by determining the set of optimal values for specified decision variables and using these to optimize the different system performance measures, such as system efficiency and environmental quality. Multi-Objective Optimization (MOO) will be the methodology implemented for the optimization of conflicting objectives taking part in the maritime transportation system. The improvement of one objective is at the expense of another hence, the answer being a set of solutions that defines the best tradeoffs between the competing objectives of maximizing the operational efficiency and minimizing environmental impacts of the

MTS. In order to validate this optimization model, the Port of Prince Rupert, BC, Canada will be used as a test case to analyze and determine optimal paths to achieve sustainability, system effectiveness, efficiency, and the impacts of this system on the natural environment. This multi-objective optimization model will be of great aid to policy makers and performance evaluators in the maritime world.

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VITA

Lizzette Pérez Lespier was born in San Juan, Puerto Rico in 1987. During her formative years, Liz's education took place at Colegio Marista of Manatí, Puerto Rico. Liz continued her education at Academia San José High School in Guaynabo, Puerto Rico.

Later on, Liz graduated in 2011 from the University of Puerto Rico- Mayagüez Campus with a Bachelor of Science in Industrial Engineering. Afterwards, Liz attended graduate school at Missouri University of Science and Technology and completed her Masters of Science in Engineering Management in December, 2013. During her Masters, Liz held a Graduate Research Assistantship under Dr. Suzanna Long where she worked on supply chain and logistics of transportation systems with a focus on system dynamics methodology.

Upon completion of her Master of Science degree, Liz decided to pursue her Ph.D. degree in Engineering Management at Missouri University of Science and Technology, to continue her research on supply chain risks, disruption and hazards. Liz received her Ph.D. in May 2017. Her research focused on the issue of environmental sustainability, assessment and control for the Maritime Transportation System. Liz implemented different decision-making and ad-hoc methodologies to measure and understand the performance of the system with regards to the environment.

Post-graduation, Liz will continue her academic career by joining the faculty of the Cameron School of Business at the University of North Carolina- Wilmington, where she expects to continue her research in the environmental aspect of sustainability in supply chains and maritime transportation system.