# A Decision Analysis Framework for Resilience Strategies in Maritime Systems


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**Abstract.** This research is an effort to develop a Risk Management-based Decision Analysis (RMDA) framework based on the common fundamental elements that define the nature of resilience in Maritime Infrastructure and Transportation Systems (MITS). The framework develops a systemic approach to the decision making process in regards to investing on resilience strategies. It also enables stakeholders and decision makers of maritime systems to identify, analyze, and prioritize risks involved in MITS operations; to define ways for risk mitigation, plan for contingencies, and devise mechanisms for continuously monitoring and controlling risk factors and threats to the system; and to value the adopted resilience investment plans and strategies. Our suggested RMDA framework is developed based on the Six-element Flexibility Framework, which is offered for assessing the value of flexibility strategies in Space Systems, and utilizes a Decision Tree Analysis (DTA) methodology for assessing the cost-effectiveness of the devised strategies.

## Introduction

### *Motivation of Research*

Maritime Infrastructure and Transportation Systems are critical and costly engineering systems that enable economic activity through the transfer of goods and services between national and international destinations. The impact of maritime systems on the economy is so essential that some consider the United States as a maritime country [1]. In 2003 approximately 95% of the volume of American overseas trade critical to nation's economic health was carried by maritime systems, mostly in containers.

American ports, as one of the major components of MITS, handle a wide variety of goods that are critical to the global economy, including petroleum, grain, steel, automobiles, and containerized goods. They also play a key role in creating jobs in all around the nation. Total ports-related employment in the U.S. was estimated at 8.4 million people in 2006 of which 1.4 million were employed though companies that provide goods and services to ports (such as longshoremen, stevedores, and security personnel) and 7 million via import/export related activities (such as transportation operators, warehousing staff, and distribution employees) [2].

Utilizing their financial, technological, and human resources, maritime systems are responsible for bringing $2 Trillion, equivalent to almost 14% of the country's GDP, in the same year [3].They handle over 99 percent of the country's overseas cargo and are responsible for transportation of more than 2 billion tons of freight and 3 billion tons of oil, each year in the U.S. The volume of trade moving through the nation's 102 seaports has nearly doubled since 1995, and by 2020, this figure is expected to be double again reaching to about 4 billion tons per year [2].

According to the reports of Federal Highway Administration (FHWA), in 2001, 38% of the total trade within the U.S. was transported by maritime systems, which includes 46% of the total annual import to the country. In the same year, the value of the trade arriving by ship was over $6 trillion that was loaded by over 500,000 non-vessel operators and 40,000 freight forwarders around the globe [4].

In addition to their importance for economy, it takes a long time to design, construct, and operationalize MITS. Upon completion, they also face a variety of operational and environmental uncertainties that can disrupt their service delivery, potentially resulting in billions of dollars of direct and indirect financial losses [5]. These threats can range from natural disasters such as hurricanes, tornadoes and floods to man-made disasters like chemical and oil spills and terrorist attacks [6].

Therefore, it is very critical for MITS to be designed and operated in such a manner that they can adopt appropriate strategies such as flexibility, resilience, and agility in the face of disturbances throughout their lifecycle. Structure of such a design is the product of a complex network of decisions that have to be made by a network of stakeholders. Thus, applying a systemic approach to improve decision making process in maritime systems can play an essential role in increasing their resilience.

## *Definition of Resilience*

The word and concept of "resilience" has been used in a variety of disciplines such as: psychology, materials science, computer networks, ecology, and organizational theory. In this research we adopt the definition of the word in the context of maritime systems as represented in the literature [7, 8]. However, this section is allocated to a brief review of several definitions of the word in other context. This review enables us to identify the commonalities in the various ways of approaching this concept.

Webster's defines resilience as an ability to recover from or adjust easily to misfortune or change [9, 10]. In psychology, the concept has been characterized as the capacity of people to cope with stress and catastrophic adversities and their level of resistance to future negative events. In materials science, resilience has been described as the physical property of a material to bounce back to its normal shape after a deformation. In computer networks, resilience has been expressed as an ability to provide and maintain an acceptable level of service in the face of faults and challenges to normal operation [11]. Finally, in organizational theory, resilience refers to the ability of an organization to design and implement adaptive behaviours matched to the immediate situational changes, while enduring minimal stress [12].

The common aspect of all these definitions is that the word has been considered as a response to unexpected or unforeseen changes and disturbances, and an ability to adapt and respond to such changes. From a managerial decision making perspective, resilience is one of the strategies that systems might be adopted or planned to utilize in the face of major disruptions. However even in the management contexts, the term has been defined and used with some similarities to several other concepts such as robustness, flexibility, adaptability, and even agility [13-15].

In this paper and in the case of infrastructural systems such as MITS, we adopt definition of resilience as a function of: system's vulnerability against potential disruption; and its adaptive capacity in recovering to an acceptable level of service within a reasonable timeframe after being affected [16-19] to make a distinction between resilience and other strategies namely robustness, flexibility, and agility that are applied by systems in face of adversity.

## Methodology

While many of the important design aspects of maritime systems address cost-effectiveness of operations and functionality of the system's components, there is also a need to assess the value of decisions in regards to incorporating strategies that are essential for keeping the entire system operational in face of adversities and disruptions. Resilience refers to capability of a system to provide and maintain an acceptable level of service in case disruptive forces are imposed to it. Resilience is a property of any complex system [20], yet planning for a more effective and efficient resiliency in a network such as Maritime Infrastructure and Transportation Systems requires investing on its design. The result of such investment will be a resilient MITS that bounce back to a predefined desired level of service in the shortest time and least crisis, mitigation, recovery management cost.

On the other hand, considering the importance of maritime systems for the nation's as well as international economy on can argue that such systems must be designed to be resilient. This necessitates investing on certain aspects of MITS's functionality during design, construction, and operating phases. In better words, resilience must be incorporated into design, structure, and operation of maritime systems. In order to incorporate the concept of resilience into the structure of MITS, first it is necessary to define its value to the decision makers and/or stakeholders of the system. This will require the development of a structure for the evaluation process as well as certain metrics that enables quantification of the problem at hand.

The U.S. Department of Homeland Security (DHS), for instance, has defined homeland security values by categorizing the structure of system's response to disruption into three major phases: *Shock Prevention*, *Vulnerability Reduction*, and *Response Preparedness* [21]. In this paper however, we categorize maritime systems' response into two distinctive areas that includes the system's reactions before and after facing disruption. We refer to these areas as: *Prevention* and *Recovery* phases. In order to lead the system out of predicament during the time that it is affected by adversities, the methodologies of Crisis Management as a discipline should be applied. Built-in resilience might well provide decision makers of the system during such turbulent times by development of right strategies. However, they are not considered a part of crisis management activities. Therefore, the suggested categorization can also delineate the scope of resilience studies for MITS.

We suggest adopting a systemic approach for making better decision on resilience investing strategies; an approach that can be used in both phases. Since resilience management has a direct relationship with vulnerabilities of maritime systems in face of environmental as well as internal threats, applying such an approach for making decisions requires a good understanding of MITS risks, specifically in the prevention phase. Based on this fact, we suggest a new framework in present research that utilizes a Risk Management (RM) approach for identification and classifying threats and combines it with Decision Analysis (DA) techniques, such as risk assessment models and the Decision Tree Analysis, as well as Systems Thinking graphical tools like cause-and-effect diagrams, as methodologies of analysis.

A framework is a basic conceptual structure, which applies systemic thinking, logic, and a variety of tools to frame and potentially solve complex issues. The proposed RMDA framework in this paper suggests a process of decision making for the prevention phase on the basis of likelihood of disruption as well as its consequences. This process is very similar to the one derived from risk assessment analysis.  We also propose the application of DTA methodology for assessing cost-effectiveness of alternative strategies [22]. However, depending on the methodologies for calculating costs and benefits of each alternative, a variety of other analytical techniques can be adopted and applied. The RMDA framework builds on insights gained from the Six-element Flexibility Framework adopted by Nilchiani [23] in assessing the value of flexibility strategies in Space Systems.

Since risk-based decision making is often an output of subjective probability analysis in general, expert probability assessment methodologies play a key role in successful utilization of RMDA framework. In particular case of MITS in which disruption might lead to catastrophic consequences, the subjective probability input is more likely unreliable as they refer to kinds of events that occur infrequently and hence on which data is scarcely available. In such circumstance, RMDA must be fed by other qualitative and/or quantitative frameworks that suggest methodologies for measuring sensitivity of such catastrophic consequences such as the one suggested by Barker and Haimes [24].

Moreover, specific methodologies have been developed for assessment the risk of terrorism quantitatively with the objective of supporting effective decision making to face terrorist attacks with catastrophic consequences [25]. While these methodologies also suggest a systemic approach to understanding the nature of threats, gathering information intelligently, and take actions based on organized and predefined procedures they focus on attacking terrorism in general and lack the inclusion of many other types of risks that threaten operability of MITS. The methodologies adopted by RMDA framework however, enable stakeholders and decision makers of the maritime systems to understand, identify, and priorities a variety of uncertainties that might cause disruption in operations of MITS and lead to catastrophic consequences.

## An Analytical Framework

Since cost-effectiveness usually plays a key role in making decisions during the process of system design and infrastructure development, articulation of a unified and comprehensive framework for measuring the multiple aspects of resilience in Maritime Infrastructure and Transportation Systems is essential for achieving a better systems-level decision making. At a strategic level, such a framework can be applied as a component of a Decision Support System (DSS) for analysis of investment strategies in MITS. In this research, we propose an analytical framework that supports making decisions on resilience strategies from a risk management point of view. The proposed Risk Management-based Decision Analysis framework, consists of three phases [7]. These include: *Assessing Vulnerabilities*, *Devising Resilience Strategies*, and *Valuing Investment Strategies*, as it is shown in Figure 1.

The first two phases mostly rely on a standard risk analysis and management approach, including effective risk assessment and control. The Assessing Vulnerabilities phase activities include identifying, analyzing, and prioritizing vulnerabilities involved in MITS operations that are considered the system's risks. Therefore, all of the qualitative and quantitative techniques and methodologies that have been developed in the literature and can applied in this phase as informational input.

The Devising Resilience Strategies phase builds on the first phase and goes on to define ways to mitigate risk, plan for contingencies, and devise mechanisms for continuously monitoring and controlling risk factors as well as threats to the system. Again, as this phase provides procedural direction to devising resilience strategies, it does not offer using any particular method and hence, all the existing developed methodologies can be adopted.

Finally, the Valuing Investment Strategies phase uses Decision Analysis tools and methodologies to assess the cost-effectiveness of the devised strategies. While many DA approaches have been developed for analysis of decisions in special cases of low probability and high consequence events, in this paper, we have used Decision Tree Analysis approach. DTA is based on applying the concept of expected value, which is known to have limited value in cases that infrequent incidents cause catastrophic consequences.

However, since this research considers the economic aspect of MITS operations, DTA could be an effective tool to show the financial aspects of resilience investment options. Moreover, since it uses a very simple and straightforward approach for evaluating alternatives, DTA can better serve all the stakeholders of maritime systems to understand the nature of resilience investment and support them to make effective decision in this regard. In the following, we will explore the RMDA framework for MITS in more detail.

**Assessing Risks**

**Step 1:** Identify the critical risks of the system

**Step 2:** Select one or more of the identified risks to the system based on priorities that have been set by its stakeholders and/or decision-makers

**Step 3:** Find the probability distribution of the most prominent risk factors of the sytem and create risk profiles for each one of the selected disruptions

**Devising Resilience Strategies**

**Step 4:** Brainstorm among stakeholders and collectively generate a set of solutions and/or strategies that can possibly increase the system's resilience

**Step 5:** Identify the costs associated with each suggested solutions and/or strategies

**Valuing Investment Strategies**

**Step 6:** Calculate the expected value of each strategy base on the created risk profiles for the disruptive events as was mentioned in step 4

**Step 7:** Calculate the expected cost of each strategy using Decision Analysis tools

**Step 8:** Create a tradespace of the strategies for the system's decision makers

**Figure 1 An Analytical Framework for Making Decisions on Resilience Strategies**

### *Phase I – Assessing Vulnerabilities*

Decision makers of maritime systems need to have a clear understanding about sources of uncertainty and possible consequences of unprotected vulnerabilities that threatens the system. This is the only way to enable the stakeholders to prevent disruptions and respond to disturbances, shocks, or incidents timely and efficiently. Risk assessment for instance is an approach that provides the decision makers with opportunities to understand the nature of risks within the system's environment and plan to deal with those risks in advance. The process of effective risk assessment should involve: identification, measurement, prioritization, management, and mitigation of all the risks. More importantly, it must be a dynamic and continual process, reviewed regularly with the purpose of meeting the required objectives of the risk management plan [26].

There are many researches that have been conducted on assessment and/or management of the risks involved with operations of infrastructures in the U.S. as a response to the President's Commission on Critical Infrastructure Protection of 1997. The commission addresses major sources of risk to the nation's critical infrastructures and also suggests some risk management options to face them. The suggested options fall into two categories: protecting infrastructural systems assets and making infrastructural systems resilient. Most of the governmental research efforts have been focused on identification and analysis of infrastructural systems' assets. Some researchers have also studied the system-level attributes that includes concepts such as emergence, resilience, and preparedness [27].

In the context of MITS, process of Assessing Vulnerabilities includes: identification of risks and threats associated with the infrastructure; and development of prevention as well as contingency and emergency plans that enable maritime systems to maintain their operation. The main objective is to prevent disruptions in a proactive way rather than to deal with emerging crisis in a reactionary manner, and thus, to be able to provide a certain level of service in the scope of system's lifecycle.

Maritime Infrastructure and Transportation Systems function in a socio-technological environment in which a complex nexus of human and organization-based entities interact with physical infrastructure and equipment as well as the natural environment to create behavioral dynamics of the entire system. Based on a complex systems perspective, we categorize the roots of uncertainty in four major groups:

- **N**atural disasters;
- **O**rganizational factors;
- **T**echnological factors; and
- **H**uman factors.

Each one of these uncertainties can have various roots, either generated by outside perturbations or created by intrinsic characteristics of the organizational and/or operational systems and within the boundary of MITS.

Human, technological, and natural factors can affect maritime systems any time and according to their probability patterns of occurrence. Therefore, we can consider them as independent causal factors. However, organizational factors usually emerge while MITS is affected by disruption and during critical phases of shock absorbance and recovery. Although organizational factors might also incur adversities, the level of their independent influence on the system is usually mild and will not lead to catastrophic consequences. However, they can incur a real crisis if they emerge during or after another catastrophic event caused by other aforementioned causal factors.

In a better word, organizational factors have a consequential nature and aggregate the effects of human, natural, and technological factors following to the occurrence of disruption. Therefore, organizational vulnerabilities of MITS namely, poor communication, lack of training, limitations of connectivity are more recognizable when the system is in trouble and already struggles with a crisis caused by the other factors. As a result, it is almost impossible to assess the organizational factors within the list of known vulnerabilities independently and not as a consequent factor. Even the subjective probability methodologies cannot be useful in quantification of these effects.

Figure 2 shows the relationship of vulnerability factors in Maritime Infrastructure and Transportation Systems.

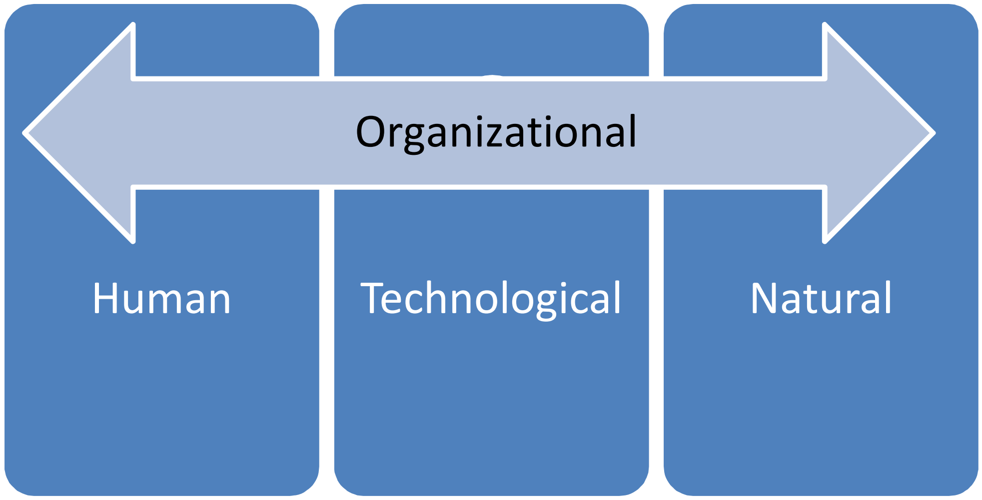


**Figure 2 Organizational Factor as a Consequential Vulnerability**

A list of threats can be identified within boundaries of the four causal categories. Human factors that might cause disruption in operations of maritime systems can be originated by several other causes such as industry actions, terrorist attacks, and human (including manager or operator) errors. Natural factors include hydrologic, geologic and seismic, and atmospheric hazards. Organizational factors might be imposed to the system by bureaucracy, poor training systems, organizational structure limitation, and security lockdowns. Finally, technological factors might trigger by computer network failure, interface issues, failure of control systems, maritime accidents, and interface issues.

It is possible to go forward in identifying more details about the causal roots for each one of these factors several layers deep. This will however need the collective input of maritime systems' experts that can be gathered through designated questionnaires or objective-oriented interviews. Development of causal roots of uncertainties could be a topic of other researches. What is essential about this approach is the fact that it creates a powerful framework for identifying risk factors in any large-scale system. In the specific case of maritime systems, we suggest that the Assessing Vulnerabilities phase to apply this technique for identification of the threats and risks MITS face. The result has been illustrated in a cause-and-effect diagram presented in Figure 3. What is presented here is only an example of how a systemic way of thinking about this matter sheds light on understanding roots of failure in maritime systems' operations.

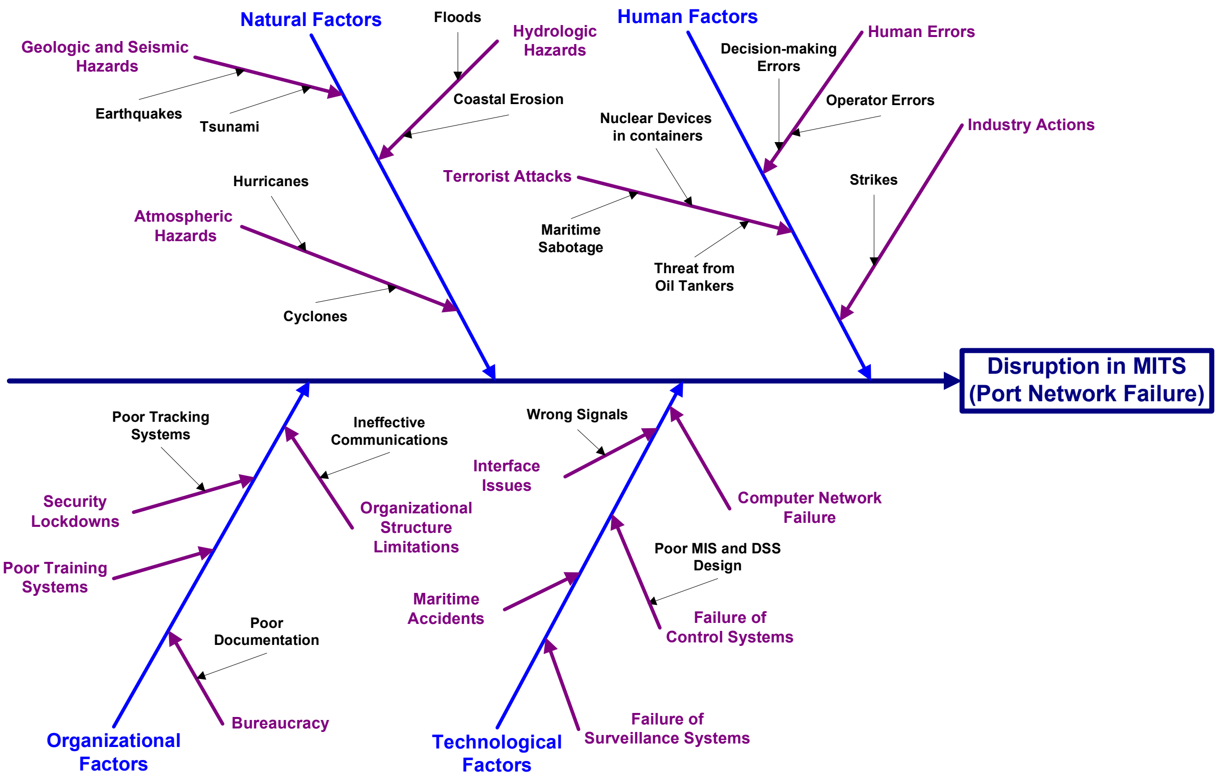


**Figure 3 The Cause-and-Effect Diagram for Disruptions in Maritime Systems**

## *Phase II - Devising Resilience Strategies*

Inspired by the resilience engineering literature, our proposed RMDA framework approaches MITS resilience through an embedded two layered strategy: one that creates a set of barriers with the purpose of buffering the system from major external and internal disruptions – absorbing shock and reducing uncertainty; and one that provides the system with applicable contingency and emergency mechanisms and plans in order to minimize the adverse consequences of those disruptions that could not be prevented – characterized as a mitigation or recovery plan. Based on a bowtie model [28] represented in Figure 4, we suggest that a two layered approach effectively increases resilience of maritime system.

The boxes represented on the left side of our bowtie model are called the *Resiliency Barriers*. According to a black box model perspective, they are considered to be interconnected constituents, each with characteristics of system that is able to operate independently. Therefore, each one of these so-called barriers may include a monitoring system enabled with sensors, connections, feedback loops, action capabilities, etc. The same is true about the depicted constituents of the right side of the bowtie model, *Resiliency Contingencies*. These blocks are representing a set of actions or reactions in the form of procedures that can be standardized as various policies. In fact, they can also be considered as interconnected systems that are supposed to run independently.

Therefore, the Devising Resilience Strategies phase should concentrate on developing series of independent system, which dynamically interact with other components of the larger system in a higher level, foresee or understand vulnerabilities of the whole complex, and provides solutions proactively, in form of preemptive and preventive actions. This, according to the literature, can be defined as a methodology for System of Systems (SoS) management [29, 30]. The choice of this approach is due to the large-scale distributed set of complex systems that are dynamic and work concurrently and in an interoperable manner. As a result, strategies that are devised to make MITS resilient should be applied in accordance to SoS management techniques.

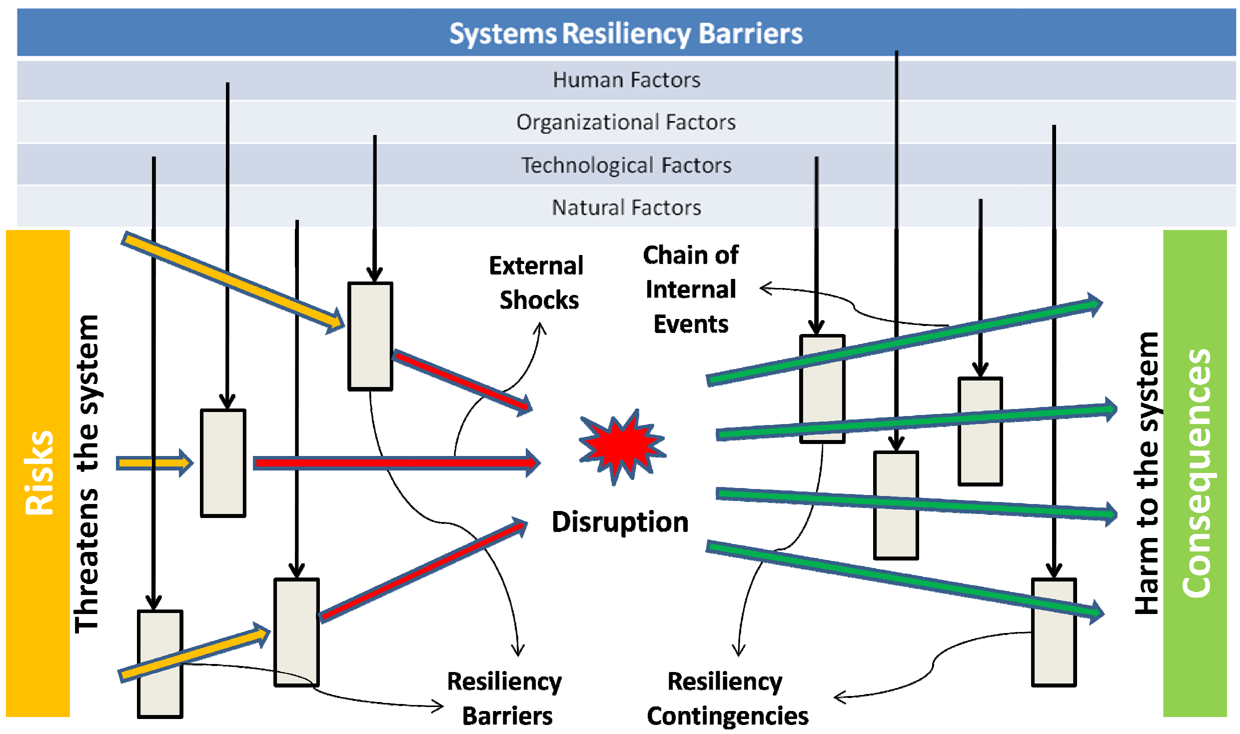


Figure 4 The Two Layered Approach to Resilience in Maritime Systems

The core of efforts for designing maritime systems to be a resilient SoS is making the entire country's economy less susceptible to major fluctuations that cause a large amount of loss annually. Thus, the criteria we have chosen in this paper for proposing resilience strategies only rely on economic factors. Implementation of such strategies requires financial investments with a possibility of long-term horizon. At the same time, it will expedite the process of maritime transportation and makes it more efficient, which ultimately contributes to economy in long run. Consequently, it is quite reasonable to make decisions based on the alternative financial outcomes. The following represent some of the resilient strategies that may be considered in the case of MITS and the reason they should be approached in a decision making context.

As an example, investing on new container tracking technologies from origin to destination with higher reliability and accuracy can be considered as a resilience strategy. Implementation of such a strategy requires a complicated system design and a sophisticated technology as well as multi-layered and international legal agreements, which are both costly and time consuming. However, the implementation of such strategy will reduce the loss of MITS stakeholders in long term. Obviously, the most important aspect that should be studied is feasibility of the strategy from an economic perspective and calculating the time at which the investment breaks even.

As another example of strategies for resiliency, we can consider the design and construction of extra facilities (such as wharfs and platforms), with the required equipment storage for making them operable (e.g., cranes and forklifts) in cases of emergency. This strategy creates resilience through redundancy in a system by providing slack capacity at a time that the system faces a major disruption, such as a hurricane, when extra capacity is needed due to lockdown of other neighboring ports.

If the understudy ports are unlikely to be affected by natural factors, such facilities can be installed completely and be ready to use at any time necessary as an extended capacity of its entire neighborhood region. Keeping a plain platform that can become operable in a short period of time might be a reasonable strategy. The only restriction is that all the necessary equipment for installation and operation of such platform must be stored nearby and decision makers must be able to transport them rapidly and cost-effectively. Again, the deciding factor would be the cost-effectiveness of each proposed strategy.

The RMDA framework suggests development of resilience strategies based on the identified risk factors and vulnerabilities of the entire MITS, provided by the first phase of the framework. This is very important as the proposed strategies must address certain issues that threaten MITS through organizational, technological, natural, and human factors. The importance of this relationship becomes clear in the third phase of the RMDA framework, where decision makers should value the proposed investment strategies in order to make the best decision. The process of valuing the proposed resilience investment strategies is meaningful only when it is based on risk assessments of the first phase.

### *Phase III- Valuing Investment Strategies*

The integration of resilience into the design and operation of the MITS can potentially be costly. However, the risk of losing the service capacity for a period of time, in face of serious perturbations may well justify the effectiveness of the design-level investment. Evaluation of cost-effectiveness in this case requires cost analysis based on risk management methodologies [31]. Within our RMDA framework, we propose the application of decision analysis techniques such as DTA or real options-based planning processes to identify cost-effective alternatives justified at each point in lifecycle of MITS with consideration of both layers of resilience factors.

With respect to resiliency of the system, one way of dealing with uncertainty and risks that threatens the system is to have built-in resiliency in the initial design, which can be expressed through strategies devised in regards to resilience. In future, somewhere down the line of system's lifecycle, such built-in resiliency enables the decision makers to adopt various effective alternatives efficiently and at relatively low cost.

However, the built-in resiliency structure of MITS imposes a combination of fixed and variable costs to the system that appear in forms of investment and maintenance respectively. That is why the Valuing Investment Strategies phase of RMDA framework is essential for making decisions in a systematic manner. As efforts in valuation of other strategies such as flexibility shows, in most cases, the advantage of certain investment options in dealing with changes in the future outweighs the expected value of performance loss [32].

In order to analyze the cost of investment alternatives in Maritime Infrastructure and Transportation Systems, we can apply decision analysis methodologies such as DTA or the economic theory of real options. In general, DA is a simple standard approach for defining a wide range of alternatives within a predetermined timeframe or over several periods. It is important to know that DA is very useful in situations where the probabilities and frequencies of risks and uncertainties are identified, understood, and known [33]. In the case of RMDA's application in MITS, understanding the nature of risks and uncertainties is a requirement that is fulfilled in the first phase of the framework. Thus, Decision Analysis methodologies discussed in the following are appropriate tools for analyzing the situation from the perspective of the RMDA framework:

A decision tree is one of the DA tools that support the process of decision making by representation of alternatives, uncertainties, and outcomes. The value of each possible outcome can be calculated, using the expected value function, which in fact, incorporates the effect of risk into the calculations indirectly [22]. Decision Tree Analysis is a useful tool in analyzing sequential complex decisions in which the representation of uncertainty is discrete in time. It is also capable of recognizing the interdependencies between initial and subsequent decisions. An optimal decision in DTA is chosen based on optimization criteria (that is usually in terms of financial loss and/or gain of the branches) through calculating the expected value of the alternatives, and working backwards in the decision tree.

However, applying DTA has some limitations as well. For example, the size of the tree expands geometrically with the number of decision nodes. Thus, applying DTA to real cases in which there are usually a lot of chance nodes and subsequently many decisions can become very complicated. The other limitation is that DTA is not a methodology to be used for uncertainties of a continuous nature [22]. Moreover, since it is developed based on the idea of expected value calculation, DTA is not considered an effective technique for the types of events with low probability of occurrence and high cost of consequences. MITS risk factors are mostly characterized as low probability and high consequence and hence are not be best represented by DTA for making decisions. Nevertheless, representation of decision trees of financial consequences can still be a very powerful to communicate with stakeholders of maritime systems and can well serve the purpose of a Decision Support System tool.

Option analysis is another methodology that can be used for analyzing decisions in a system. An option is defined as the capability of decision makers to take (or leave) some action at a certain time in the future. In fact, although there is a value assigned to each option that can be bought or invested at some time in the past, the decision maker is not obligated to use it in the future [33]. This concept has had a huge impact on the approach to project investment and moreover, it can be incorporated in management of risk and analysis of uncertainties that threaten the functionality of a large system or an infrastructure.

Option analysis has also been applied to the management of flexibility in complex systems [22]. This methodology and its relevant evaluation techniques were created in the field of finance, for the first time [33]. However, the concept of options can be used as a strong tool in analysis of decision in the same way. Solving a real option problem is to some extent more complicated in comparison to DTA calculations and is usually possible through application of numerical methods, using partial differential equations or in some cases, Monte Carlo simulation.

Beside the aforementioned two techniques, there are also many others that have been developed and are more appropriate for decision making within the environment of maritime systems. Although the RMDA framework does not specify choosing any specific methodology, we suggest the application of DTA or real options techniques in Valuing Investment Strategies phase of the framework. This idea is proposed based on the fact that these methodologies are easy to use and more straightforward; hence, they can be used as a communication tool with high-level decision makers in any large-scale system. Exploration of other decision making methodologies, especially those that are known to be more effective to MITS will be done in future researches.

The first two phases of RMDA framework help us to understand the nature of uncertainties that may cause major disruptions in Maritime Infrastructure and Transportation Systems. They also develop strategies that can be devised for and implemented in MITS to decrease vulnerabilities of the system against threatening risks. At the same time, these phases facilitate the process of bringing back the maritime systems to a satisfying level of service. While the first two phases enable us to structure the maritime systems' resilient strategies, the third phases is about valuing these strategies based on existing Decision Analysis methodologies and comparing the value of each strategy with the alternative of avoiding resilience investment.

In order to do that, it is necessary to have financial information about the cost of built-in resiliency investment options as well as the economic impacts of losing a portion or the whole capacity of MITS components due to facing a major disruption. Unfortunately, there are little documentations available in this regard, which makes obtaining such information very difficult. In fact, in particular case of maritime systems such information either does not exist, or is not available due to the sensitivity of the issue.

Taking these limitations into account, in order to represent the way RMDA framework helps maritime systems' stakeholders to make resilience-related decisions we generate some information partly based on available public resources and partly through intuitive conclusions for the Port of Boston. This will provide us with opportunities to apply our proposed framework and observe the results in terms of resilience strategies decision making. The next section is dedicated to the development of a case in which RMDA framework is applied for Decision Analysis process for the proposed resilient strategies.

## The Port of Boston's Case

The Port of Boston (PoB) is one of the larger ports in the United States with more than 21.8 million metric tons of cargo transferred every year [34]. The PoB's activities are supported by the Massachusetts Port Authority that owns, leases, and operates approximately 500 acres of property that are restricted to maritime industrial activities and located in East and South of the State. As a growing port, the PoB serves the nation through its Conley Container Terminal, Cruise Port, and Boston Auto Port.

Conley Container Terminal is the center of Boston's extensive cargo handling network. The terminal is designed to offer continuous and simultaneous port services, specifically loading and unloading of multiple container ships. This enables the port to operate at a speed equivalent to those of the biggest ports on the North Atlantic. The Conley Container Terminal is also able to serve the largest container ships in service on the Atlantic, with four post-Panamax container gantry cranes and berths 45 feet deep [35]. The activities of the PoB during 2006 and 2007, which are represented in Tables 1, indicate the importance of the PoB for the nation. That is why we chose this port as our case study.

**Containerized Cargo: Public and Private Terminals**

| | ***2006*** | ***2007*** | ***Change*** |
|---|---|---|---|
| | 902,473 | 1,113,654 | 23% |

| | | | |
|---|---|---|---|
| Import Metric Tons | | | |
| Export Metric Tons | 538,257 | 620,303 | 15% |
| Total Containerized Cargo | 1,440,730 | 1,733,957 | 20% |
| Container Ships (includes barges) | 259 | 361 | 39% |
| Auto Vessels | 18 | 20 | 11% |

**Bulk Cargo Imports in Metric Tons**

| | *2006* | *2007* | *Change* |
|---|---|---|---|
| Automobiles (Autoport) | 13,226 | 12,095 | -9% |
| Petroleum Products | 8,876,924 | 7,679,205 | -13% |
| Salt | 653,501 | 715,339 | 91% |
| Liquefied Natural Gas | 2,564,566 | 3,154,858 | 23% |
| Gypsum | 154,560 | 159,055 | 3% |
| Cement ** | 184,492 | 257,508 | 40% |
| Other | 776,734 | 1,223,565 | 58% |
| Sub-total Bulk Imports | 13,224,003 | 13,201,625 | 0% |

**Bulk Cargo Exports in Metric Tons**

| | *2006* | *2007* | *Change* |
|---|---|---|---|
| Scrap Metal | 648,279 | 539,966 | -17% |
| Other | 19,958 | 35,463 | 78% |
| Sub-total Bulk Exports | 668,237 | 575,429 | -14% |
| Total Bulk Cargo | 13,892,240 | 13,777,054 | -1% |
| Bulk Cargo Vessels/Arrivals | 478 | 481 | 1% |

**Total Port of Boston Cargo: Container, Automobiles, Passengers**

| | *2006* | *2007* | *Change* |
|---|---|---|---|
| Total Port of Boston Cargo | 15,332,970 | 15,511,011 | 1% |
| Container TEUs (Fulls Only) | 162,144 | 223,393 | 1% |
| Automobiles Processed (Units) | 12,149 | 10,079 | -17% |

| | | | |
|---|---|---|---|
| Cruise Passengers | 208,883 | 234,284 | 12% |
| Cruise Vessel Calls | 81 | 101 | 25% |

Table 1 Port of Boston's Activities [35]

In the following, we apply the RMDA framework using the three phases explained in section 3. The idea is to assess the port infrastructure vulnerabilities; provide resilience strategies to control them; and finally value each one of these suggested strategies. The lists of the system's vulnerabilities and resilience strategies that are presented in this example are neither inclusive nor exhaustive of all the possibilities. The objective is not to decide about the resilience strategies for the PoB. Rather, we would like to demonstrate how the proposed framework can be applied to similar situations by the stakeholders.

### *Phase I – Assessing Vulnerabilities at the Port of Boston*

In order to assess the vulnerabilities of the PoB, we should explore different types of risks per the four categories identified in section 3.1, namely human, organizational, technological and natural risks. However, since organizational factors are consequential to the other three categories and thus very difficult to assess, we exclude them from this analysis here. Table 2 lists some of the PoB key vulnerabilities that might be identified by stakeholders under each category.

| Category of Vulnerabilities | Threat | Likelihood (1-5 Scale) | Impact (1-5 Scale) | Risk Factor |
|---|---|---|---|---|
| **Human** | H1 – Terrorist attack on the port's infrastructure using nuclear device in container | 1 | 5 | 5 |
| | H2 – Terrorist attack using tanker collision with Liquid Natural Gas (LNG) storage tanks in harbor | 2 | 5 | 10 |
| | H3 – Chemical spill resulting from maritime accident in harbor | 3 | 2 | 6 |
| **Technological** | T1 – Failure of Port Information System (PIS) or the computer network shutdown | 2 | 4 | 8 |
| | T2 – Malfunction of processing as well as security facility equipment | 1 | 3 | 3 |
| | T3 – Failure of ship navigation or waterways control systems | 2 | 2 | 4 |
| **Natural** | N1 – Hurricane Category 3 or less | 2 | 3 | 6 |
| | N2 – Hurricane Category 4 or higher | 1 | 5 | 5 |
| | N3 – Snowstorm limiting functionality and visibility | 4 | 2 | 8 |

Table 2 The Port of Boston's Key Vulnerabilities

As it is presented in Table 2, we have only included three major threats under human, technological, and natural categories in this example. The likelihood and impact of each threat are rated in a 1 to 5 scale (in which 1 is the lowest and 5 refers to the highest intensities), based on common sense and a subjective judgment. The risk factor is calculated by multiplication of likelihood and impact of each threat. Calculation of the risk factor can be used to prioritize the threats as explained in section 3.1. Thus, in this example, decision makers might choose to develop related costs and resilience strategies only for H2, T1, and N3. However, conducting cost analysis for all resilience strategies broaden the space of decision making and enable the authorities to make the right decisions, following the guidance of RMDA framework and based on availability of the budget.

Table 3 represents the estimated costs associated with the selected threats in million dollars. The information used in the table is either extracted from available public documents, based on the reported statistics on the PoB, or determined subjectively. The figure under the column of "Estimated Number of Human Life Loss" refers to the number of people that might be killed because of each incident and "Estimated Monetized Human Life Loss" is the monetized value of each person's life. Following the same logic, "Estimated Operational Day Loss" is an average of the days that the port stops operating, while "Estimated Operational Loss Per Day" represents the monetized value of each day lost.

| Threats | Estimated Number of Human Life Loss [36, 37] | Estimated Monetized Human Life Loss [38] | Estimated Infrastructure Capital Loss | Estimated Operational Day Loss | Estimated Operational Loss Per Day [35] | Total Monetized Loss |
|---|---|---|---|---|---|---|
| **H1** | 225,000[1] | $ 8.08[2] | $ 700 | 90 | $ 5.5[3] | $ 3,013,000 |
| **H2** | 90,000[4] | $ 8.08 | $ 500 | 90 | $ 5.5 | $ 1,722,200 |
| **H3** | 0 | $ 8.08 | $ 100 | 20 | $ 5.5 | $ 210 |
| **T1** | 0 | $ 8.08 | $ 5 | 10 | $ 5.5 | $ 60 |
| **T2** | 0 | $ 8.08 | $ 10 | 10 | $ 5.5 | $ 65 |
| **T3** | 0 | $ 8.08 | $ 5 | 10 | $ 5.5 | $ 60 |
| **N1** | 50 | $ 8.08 | $150 | 5 | $ 5.5 | $ 581 |
| **N2** | 600[5] | $ 8.08 | $350 | 60 | $ 5.5 | $ 5,528 |
| **N3** | 0 | $ 8.08 | 0 | 2 | $ 5.5 | $ 11 |

Table 3 Estimated Costs of the Selected Threats to the Port of Boston

Based on the numerical assumptions, these threats might cause a range of financial loss for the port from 11 million dollars in the case of known threat of snowstorm to about 3 trillion dollars in the case of a serious nuclear attack.

## *Phase II - Devising Resilience Strategies for the Port of Boston*

According to the RMDA framework, after identifying the vulnerabilities and calculating costs associated with each one of them, the next phase is proposing resilience strategies. These strategies should be usually created by the decision makers, stakeholders, and authorities at the PoB by taking the considerations of decreasing and/or controlling vulnerabilities as well as

[1] This is 5% of the estimated population of Boston Metropolitan Area in 2000.
[2] This is the average of the life value estimation in a discussion paper at Harvard's law school.
[3] This amount is calculated based on the claim that PoB contributes more than $2 billion annually to the local, regional, and national economies through direct, indirect, and induced impact.
[4] This is 2% of the estimated population of Boston Metropolitan Area in 2000.
[5] This number is selected based on the statistics of New England Hurricane in 1938.

increasing the port's adaptive capacity into account. The resilience strategies suggested for the case of PoB are represented in Table 4 in which all the numbers are in million dollars.

| Threats | Resilience Strategies | Description | Estimated Cost of Strategy |
|---|---|---|---|
| **H1**<br>**H2**<br>**H3** | R1 – Integrated security and safety design | Design and implement a security system that monitors the cargo throughout the entire process of maritime transportation from manufacturing firm at countries of origin to the port of destination. | $150 |
| **T1**<br>**T2**<br>**T3** | R2 – Technological redundancy investment | Provide the possibility of redundancy for the information systems of the port and waterway control systems of the ships. Design an effective support and maintenance system for facilities of the port. | $20 |
| **N1**<br>**N2**<br>**N3** | R3 – Infrastructural redundancy and support investment | Maintain a set of operational equipment in a secured area and construct ready-to-use-platforms that can be operationalized timely and efficiently at the time of natural disruptions | $ 250 |

**Table 4 The Estimated Cost for Selected Resilience Strategies**

It is very complicated to calculate the cost of each resilience strategy. The procedure should be based on the records of similar investments in the past, normalized with the effects of economic factors such as inflation and adjusted by the time-value of money. Such calculations must be done by the authorities and experts within the industry. The estimated costs presented in this phase have been suggested subjectively only to be used in exemplification of the RMDA framework procedure.

## *Phase III- Valuing Investment Strategies at the Port of Boston*

When vulnerabilities are identified, categorized, prioritized, and selected; then resilience strategies and their associated costs are provided by authorities; structured decision making methodologies must be applied to provide a support system for choosing alternatives. While a range of different methodologies can be adopted, in this case we use Decision Tree Analysis for calculating the expected value of cost facing each disruptive event, which is explained in Table 2 and make investment decisions based on estimated costs of resilience strategies.

The structured methodology of DTA will enable us to create a trade space of resilience strategies for the decision makers based on which they can evaluate their alternatives. Moreover, adopting a decision analysis approach will allow us to run sensitivity analysis by changing estimated costs, probabilities of occurrence, and all other variables as well as scenario analysis by making changes in premises and suppositions. Figures 5, 6, and 7 are the simplified decision tree representations for each one of resilience strategies against disruptive events caused by the identified vulnerabilities for human, technological, and natural factors.

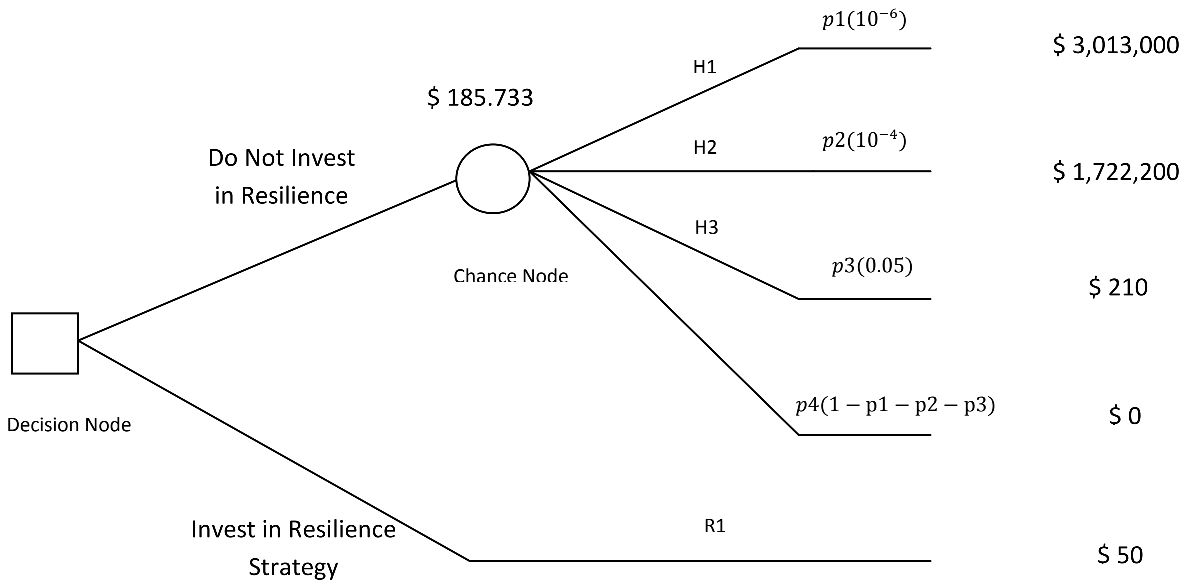


Figure 5 Decision Tree for R1 versus H1, H2, and H3

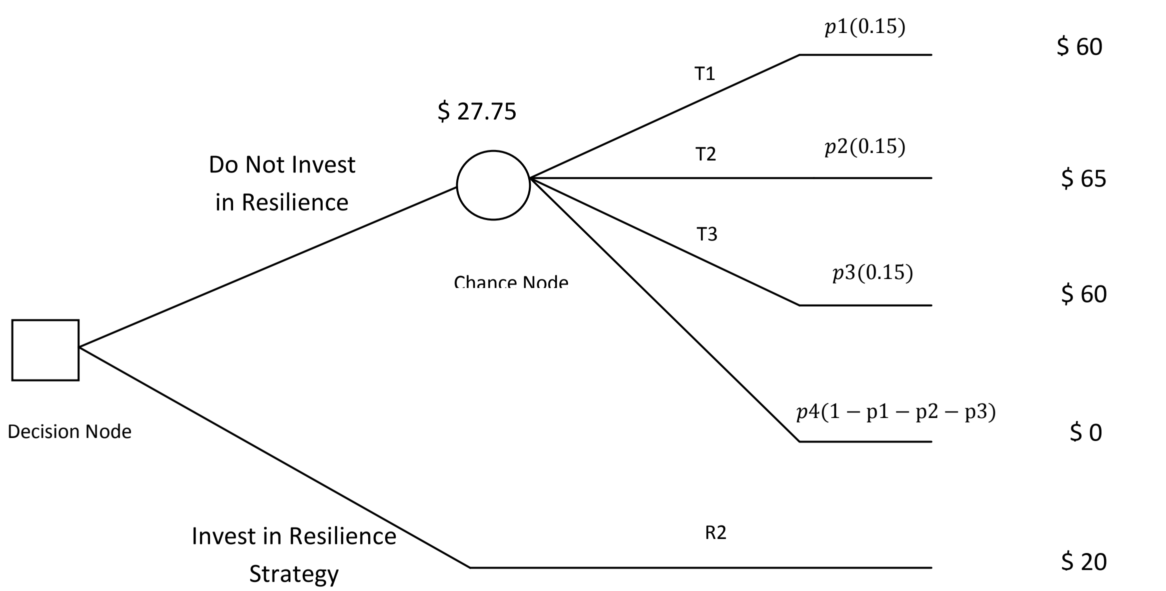


Figure 6 Decision Tree for R2 versus T1, T2, and T3

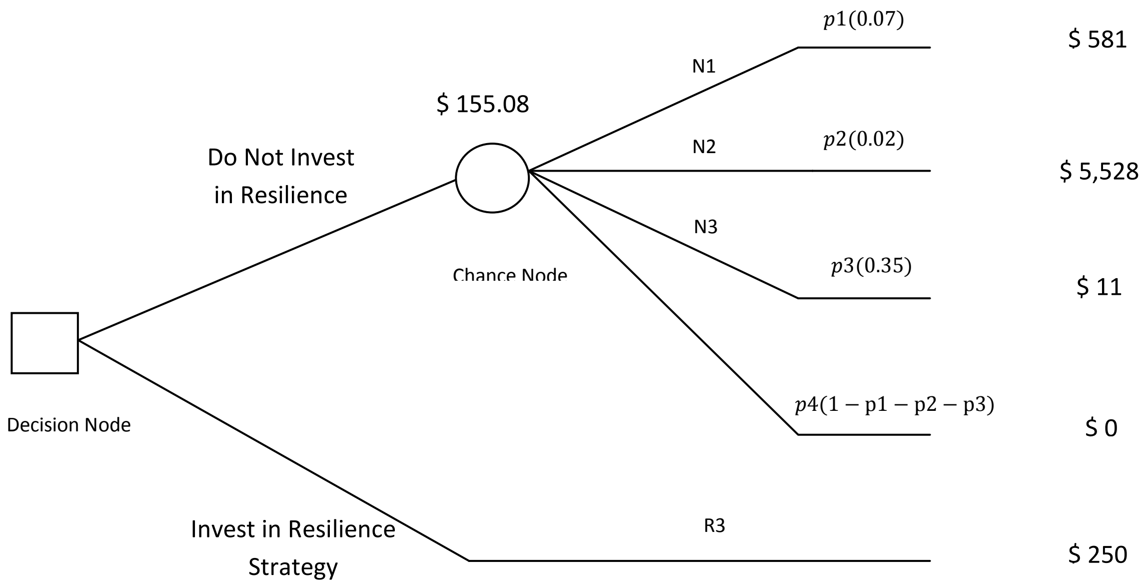


Figure 7 Decision Tree for R3 versus N1, N2, and N3

Based on a DAT methodology and as depicted in Figures 5-7, investing in resilience strategies of R1 and R2 is less costly than buying the risk of vulnerabilities for human and technological factors. Therefore, adopting R1 and R2 is suggested. However, the expected value of risk costs for natural factors is less than the required investment budget to adopt R3. As a result, the decision makers might want to buy the risks of natural factors with only a portion of their investment budget.

There are obviously many other concerns in making such decisions for an industry like maritime transportation at the Port of Boston. Factors such as long term economic effects of these decisions, technological advancements impacts on ports and their related industries, as well as, legal, safety and security policies make big differences in the process of decision making. Yet, applying structured and systemic methodologies such as the proposed RMDA framework as part of stakeholders' DSS tools is crucial for making the decisions and choosing the best alternatives.

## Conclusion and Future Research

There is a lack of an effective framework that incorporates the effects of risks involved in Maritime Infrastructure and Transportation Systems, specifically for decision making about the existing resilience investment strategies. Using the proposed Risk Management-based Decision Analysis framework we suggest identification of the common elements of uncertainty in MITS, which sheds light on maritime systems' response to disruptive events through data analysis. The RMDA framework also provides opportunities to evaluate the costs associated with probable failures, which might be caused by disruptive events through simulation and modeling. It also can enable the stakeholders to calculate an estimate for the cost of investing in resilience strategies.

The framework is developed based on a risk analysis and management approach, which help us to understand the nature of uncertainty in maritime systems in a structured way and consequently enables us to devise resilience strategies in regards to the known vulnerabilities of the system. The proposed RMDA framework then uses decision making analysis tools to choose among investment alternatives regarding resilience strategies and in three major phases.

In the first phase, risk assessment methodology is applied to understand the nature of uncertainties through identifying, analyzing, and prioritizing risks of MITS. The second phase, applies the cause-and-effect diagram methodology to create a tree of events and their probable effects, which can be used as a tool for devising resilience strategies that avoid disruptions to the system. Finally, the third phase uses decision analysis methodologies to evaluate each strategy's value for the entire system. This phase provides guidance for decision making about infrastructural investments by comparing the value of alternatives with the economic consequences that the system has to face as a result of lacking the resilient strategies that those investments address. We suggested Decision Tree Analysis and Real Options Analysis as analytical tools that can help decision making in this phase. This does not mean that these methodologies are necessarily the most effective ones; rather, it shows the way Decision Analysis tools can be applied in this phase.

In order to provide a numerical example of how the RMDA framework can be used in strategic decision making regarding to MITS resilience, we also developed a case study based on situation and characteristics of vulnerabilities as well as strategic possibilities of investment at the Port of Boston. Preliminary results show that the strategies, which reduce vulnerability of the port in face of disruption, are far more cost-effective and feasible than those suggesting the system's recovery after being affected. According to the example of the Port of Boston's case, since facing disruption in MITS is inevitable, integration of well-designed contingency plans for mitigation and recovery, as it is also suggested by others [39], is essential for increasing resiliency in such a complex system.

There are opportunities to extend this research by adopting more effective methodologies for risk assessment and analysis as well as for decision making. This may include consideration of applying several methodologies to the same problem and comparing the results. The output of such collective approach can be used as a part of the MITS' Decision Support Systems that helps stakeholders to consider all different aspects of resilience strategies before making investment decisions. Since the framework does not specifies applying any particular methodology neither for the risk assessment and management phase nor for the decision making and analysis step, future attempts to adopt and test a variety of existing methodologies will bring new meanings to the context of systemic decision making within the realm of maritime systems.

Taking the sustainability of MITS into account, could be another interesting extension to this research. According to the studies, by the end of $21^{st}$ century, nearly two third of the national population in the United States will live along the coast, mostly in urban centers and along watercourses. Share of MITS in economy will increase to 50% of the GNP and thus, there should be an enormous investment in the coastal zone and maritime infrastructure, especially where the existing coastal ecosystems are in the critical thresholds of repair or even beyond [40]. Considerations of inevitable environmental issues, caused by the ports in financial analysis of investments as an important factor for the resilience of MITS should be addressed in future studies.

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