Risk-Based Marine Inspection Performance Measures

An Interactive Qualifying Project
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Abstract

The objective of this project was to standardize the way risk reduction is measured during marine vessel inspections, based on the deficiencies found on each vessel by the Coast Guard. Over the course of the project, we researched past performance measure models, in addition to working closely with the MISLE database and Coast Guard personnel to determine which factors should be included in our analysis. We then created a prototype model, based on the vessel data from the past decade, for automatically assigning risk-reduction values to various deficiencies.

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List of Abbreviations

ABS – American Bureau of Shipping

AV – Accident Value

AWO – American Waterways Operators

CCC & IT – Command, Control, Communications and Information Technology

CGBI – Coast Guard Business Intelligence

CVC – Commercial Vessel Compliance

ETA – Event Tree Analysis

FMEA – Failure Modes and Effects Analysis

FORCECOM – Force Readiness Command

FTA – Fault Tree Analysis

HR – Human Resources

IEC – International Electrotechnical Commission

IHI – Institute of Health Improvement

IQP – Interactive Qualifying Project

ISM – International Safety Management Code

ISO – International Organization for Standardization

ITB – Integrated Tug and Barge

MISLE – Marine Information for Safety and Law Enforcement

MMS – Mission Management System

MSRAM – Maritime Security Risk Analysis Model

RIA – Risk Indices Analysis

RPN – Risk Priority Number

RRV – Risk Reduction Value

SME – Subject Matter Expert

TSAC – Towing Safety Advisory Committee

TVNCOE – Towing Vessel National Center of Expertise

USCG – United States Coast Guard

WPI – Worcester Polytechnic Institute

Executive Summary

The United States Coast Guard (USCG) is phasing in a new set of regulations requiring annual inspections for towing vessels, a category of vessels which have not been previously subject to Coast Guard inspection. To maximize the value of these new regulations, it is important for the Coast Guard to assess their performance during towing vessel inspections, and quantify their level of preventative measures to better allocate both time and resources. Currently, no systematic method of accomplishing this task exists.

The Coast Guard's Prevention mission performance has historically been measured and reported in terms of "tombstone parameters" that have included annual statistics of deaths and casualties. This information did not provide a complete and accurate picture of all the measures taken by the Coast Guard to create a safer marine environment, nor did it account for the fact that most accidents are not caused by a lack, or poor quality, of inspections. Therefore, the Coast Guard set out to develop a risk-based performance-measuring model that would create a method for systematically measuring risk reduction achieved through vessel inspections. To complete this task, this project centers on the assumption that each vessel deficiency has a Risk-Reduction Value (RRV) based on the amount of risk potentially prevented through the discovery of a deficiency. One may find the overall risk reduced through vessel inspection of any given vessel by summing the total risk reduction values from discovered deficiencies.

The goal of our project was to create a methodology for systematically assigning RRVs to vessel deficiencies. We accomplished this by first gaining a better understanding of risk-based analysis through research of past, successful performance measures. We then accessed the

Coast Guard's Marine Information for Safety and Law Enforcement (MISLE) Database and analyzed towing vessel data from the past decade. In order to better gauge the severity of each deficiency, we tracked trends such as frequency of incident occurrence and deficiency detection in inspection reports. Figure 1, below, helps depict how the RRV model incorporates frequency and severity to calculate the RRVs.

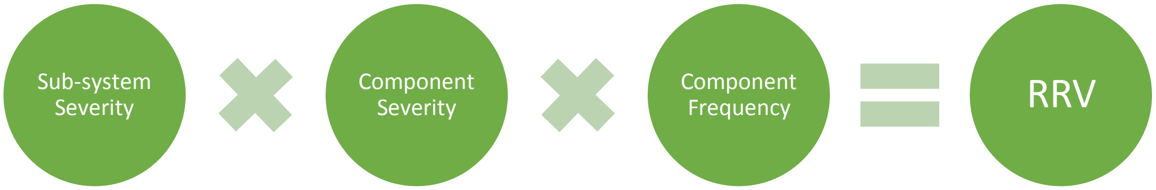

Figure 1: RRV Process

We then completed our model by adopting useful ideas from past methodologies and customized the model to best tailor it to vessel inspections. We initially tested the feasibility of our prototype by applying it to towing vessel data. The Coast Guard expects to run larger scale tests, and implement a front end for the program, eventually connecting to all vessel inspections. We anticipate that our findings and recommendations will help the Coast Guard fulfill their Prevention mission and lower the casualties and expenses associated with vessel incidents.

Chapter 1: Introduction

As part of its Prevention mission, the United States Coast Guard (USCG) (2013) recently created an annual inspection system for towing vessels, with plans for implementation in 2015 (P. Lee, personal communication, Sept. 17, 2013). While there were no previous formal USCG inspection processes in place for towing vessels, a bridging program was initiated to phase in regular inspections over the course of the past few years. As a result this will allow the Coast Guard to measure the value of the new regulations by comparing inspection data before, during, and after the bridging program.

With these new regulations in place, the Coast Guard hopes to lower marine casualties and financial losses through preventative measures which will anticipate and address problems before incidents occur. However, without a system in place that can utilize the data from the new inspection program, and compare it to data from the years prior to inspections, determining the true value of new regulations will be difficult (Talley, Jin, & Kite-Powell, 2007). Despite having extensive vessel and inspection information on hand, no distinct process has yet been created to accurately measure the performance of the new inspection system.

In past attempts at gauging the value of the inspections, data on vessel safety were based on “tombstone parameters” of numbers of casualties and property damage after an accident had occurred. While these are informative indicators of what accidents have happened, they do not directly indicate the effectiveness of the preventative measures. Because prevention extends beyond directly stopping an incident and involves identifying and diminishing certain risky conditions and circumstances, the Coast Guard’s performance must be measured in another way. For this reason, the Coast Guard aims to create a more comprehensive performance measuring system to gauge the efficiency of inspections and understand how their efforts and resources can be better spent and distributed, as well as to demonstrate the progress made as a result of the new inspection system.

To reach this goal, a system for keeping track of deficiencies found during inspections, as well as their severity, has been recently proposed by Coast Guard officials (Mission Management System Staff, 2013). This system is risk-reduction based, and assigns numerical values to different deficiencies found during examinations. The overall risk-reduction is then calculated by adding up all deficiency values. However, these individual risk-reduction values (RRVs) are currently subjectively assigned on a scale from one to ten based on the opinions and knowledge of the best estimations of the experts who got started on developing the performance evaluation system.

In order to measure the effectiveness of the new inspection program with precision, the method for assigning reduction values needs to be designed in an objective and systematic fashion. To fulfill this goal as part of our project, we examined how prior, successful performance measuring programs accomplished this task, which could aid in creating an improved process for marine vessel inspections. We initially narrowed our focus by analyzing towing vessel data within the Marine Information for Safety and Law Enforcement (MISLE) database from the past five years for test purposes, and then applied our method to the past five years of deficiency data for all vessel types. This ensured that the methodology for this process is sustainable enough to apply to other types of vessels or facilities as well as to enable our product to have more expansive application and maximize value for the Coast Guard's Prevention mission.

Chapter 2: Background

In order to ensure that all commercial vessels operating in U.S. waters meet minimum operational and safety requirements, the Coast Guard has put in place a variety of regulations, outlined in Title 46 of the Code of Federal Regulations (USCG, 2013). This chapter reviews the current vessel regulations, types of vessels, the general inspection process, and the changes made to the new inspection system for towing vessels. It then proceeds to look at prevention methods and evaluate ways by which we can quantitatively gauge risk-based performance measures.

2.1 Vessels and Inspections

Understanding vessels and the criteria used to inspect them is a necessary starting component to our project. Most commercial vessels are regulated by the Coast Guard and inspections are used to ensure regulatory compliance. Unlike other types of vessels, towing vessels are unique because they are currently uninspected. Thus, regulations are not evenly enforced throughout the towing vessel industry (S. Jason, personal communication, October 2, 2013). The new inspection system, which is planned to be fully implemented in 2015, will help in achieving better enforcement and safer waterways. This section provides an overview of regulations, types of vessels, and the inspection system process.

2.1.1 Vessel Regulations

Commercial vessels are regulated from the moment the plans for vessel construction are completed. The Coast Guard then continues to oversee vessel construction by qualified

Coast Guard Inspectors or by a designated recognized organization called a Classification Society (USCG, 2013). Once the vessel is completed, final inspections are completed and required documentation is issued to the owner/operator. This issued documentation is proof for the owner or operator that the vessel is certified for the intended service. During the vessel's life, the vessel will be periodically inspected and examined, which evaluates the fitness of the vessel to continue service. For example, a vessel designed to carry oil, undergoes rigorous inspections to ensure that the cargo tanks are intact and properly maintained. This will aid in preventing the possibility of an accidental discharge (J. Buck, personal communication, December 1, 2013). Inspectors must make sure that the vessel is able to operate safely without presenting a hazard to navigation. The scope of each inspection often includes a systematic check of most interior voids, as well as conducting an external exam of the vessel's hull, in addition to vital vessel systems necessary for safe operation. Upon completion of this inspection, the inspector will endorse some of the documentation of the vessel to indicate that the vessel can continue service until the next scheduled inspection.

2.1.1.1 Vessel Equipment Regulations

U.S. regulations require the inspection of engineering systems, materials, tools, safety devices, and other key components necessary for safe operations installed onboard each inspected vessel (USCG, 2009). These inspection requirements are mandated to ensure that the vital systems on vessels will perform as intended in case of an emergency. It is important to reiterate that Coast Guard regulatory oversight of vital vessel systems begins at the vessel's design and construction, when the materials and methods used must initially be approved. Thereafter, the installation and maintenance of machinery is regulated through approvals, tests, and inspections. The extent of regulation may depend upon how critical a system component is in relationship to the safe operation of the vessel; and to the degree of failure of the component that may contribute to a significant or major marine casualty. Other parts subject to regulation include auxiliary machinery, boilers, spill valves, emergency lighting, power equipment, and various vessel specific tools such as welding gear and petroleum related machinery. Lifesaving equipment has stringent regulations and failure to meet these requirements often mandates reporting the failure, which could lead to an investigation as to why the established standards were not met.

2.1.1.2 Accidents due to Human Error

Because accidents are not always caused by physical damage to a vessel, or by the absence or failure of equipment, the human factor must be taken into account as well. In current inspections, emphasis is put on the certification and verification of the mariners who work on commercial vessels (USCG, 2000). The type of professional credential a mariner holds determines what type of vessel on which he or she will work. Additionally, regulations concerning the length of a watch by a single crew member must be followed, such as the established three watch system on Commercial Fishing Vessels, unless licensed to do otherwise. There are also voluntary programs, such as The Crew Endurance Management System, that allow for vessel owners and operators to identify risk factors in crew endurance and ways to manage these risks.

All of the regulations mentioned above aim to prevent the most common causes of accidents: human error and equipment malfunction (Rothblum, 2000). Despite the implementation of regulations governing mariner activity and the technological advances in marine vessel construction, the accident rate remains relatively high. For example, between 2000 and 2012, there were a total of 2,365 medium to high severity incidents involving towing vessels. This means that the impact of each incident involved costs of $50,000 and higher, and/or injuries ranging in severity from those that involved professional treatment, up to hospitalization, or even death (AWO, 2013). These accidents included fires, collisions, tanker accidents, towing vessel groundings, and collisions. Looking at statistical data, human error appears to play a significantly larger role in compromising vessel safety than any other risk factor. In fact, research suggests that 75-96% of casualties are human error related, such as 75% of fires and explosions, as well as 89-96% of collisions, in addition to other types of accidents (Rothblum, 2000).

2.1.1.3 American Waterways Operators

The American Waterways Operators (AWO, 2013) is the national association for towing vessels and barges. The mission of the AWO is “to promote the long term economic soundness of the industry, and to enhance the industry’s ability to provide safe, efficient, and environmentally responsible transportation, through advocacy, public information, and the establishment of safety standards” (About, AWO). The AWO has a Responsible Carrier Program which builds upon and exceeds the government regulations and is available for companies to opt into in order to enhance their credentials by assuring that they meet the heightened standards of the AWO. The program is a good option for towing vessel companies because this program is uniquely tailored to the industry. Along with this program, the AWO ensures safety for towing vessels through their partnership with the Coast Guard and through safety committees.

The AWO has become increasingly involved and concerned with security measures since September 11, 2001. With the Coast Guard and the U.S. Army Corps of Engineers, the AWO (2013) developed a security plan for risks associated with towing hazardous cargo. In 2002, AWO released the first Alternative Security Program, which is Coast Guard approved under the current regulations. This security program includes annual audits and requirements such as security drills and exercises, security system and equipment maintenance, responding to changes in the prevailing Coast Guard-established Maritime Security Level, and security measures for cargo handling.

2.1.2 Types of Vessels

There are a multitude of vessels that travel in the waters around the U.S. This includes, but is not limited to, towing vessels, passenger vessels, cargo vessels, and fishing vessels. These vessels all have a basic structure in common, but each has a unique purpose. The vessel's purpose is what defines how and where the ship will operate.

2.1.2.1 Towing Vessels

A towing vessel has many roles and can operate in a variety of water ways (Marine Insight, 2010). Towing vessels are mainly responsible for moving other vessels that are unable to move themselves, or are unable to safely maneuver in tight spaces. This requires towing vessels to have a variety of different sizes and engine capacities and to be able to work in different environments. Each role, as well as location, imposes different risk factors and size requirements on the vessels.

One location where towing vessels operate is in harbors. There they are responsible for moving much larger vessels, as these vessels generally move forward and backwards easily, but have large turning radiuses and are generally unable to maneuver sideways (Marine Insight, 2010). Therefore, harbor towing vessels have much more power, generally around 27,000 horse power engines, than other towing vessels which have between 680 to 3,400 horsepower.

Towing vessels have the ability to operate in narrow and shallow waters (Pearce, 2005). This makes them an ideal choice for moving cargo up and down navigable rivers. They generally do this by towing barges, which are unable to move on their own. Most barges are not as big or as heavy as cargo ships, therefore river tugboats generally have less horsepower than ocean tugs, usually between 680 to 3,400 hp.

2.1.2.2 Other Vessels

Other vessels such as cargo, passenger, and fishing vessels also exist. Their purposes however, do not involve moving other ships (USCG, 2013). A passenger vessel's main purpose is to safely transport people from place to place. Their size varies depending on how many people they are intended to carry. Cargo vessels are similar to passenger vessels, except, instead of transporting people, they transport goods. Cargo vessels have dedicated, yet limited accommodations for the crew.

2.1.3 Inspection System

Various areas on a vessel, along with its equipment, are inspected during a typical vessel inspection. The USCG (2013) divides the inspection process into these main categories:

- Credentials, documents, and records
- Navigation safety equipment
- Lifesaving equipment
- Towline and terminal gear equipment
- Pollution prevention equipment
- Firefighting and prevention equipment
- Hazardous conditions.

Using a comprehensive inspection checklist with these headings, either a third party inspector or a Coast Guard inspector, goes through each applicable component to determine if the component is in satisfactory condition. Any time a deficiency is found, it is included in the inspection report and related to a specific component of the vessel. At the end of the form, there is an area for the inspector to make notes on the deficiencies of the vessel and also a section for notes and recommendations.

Vessels are inspected on a regular basis that is tailored to the specific type of vessel. Many of the inspections done on certain large commercial vessels are performed by a third party, called a Classification Society, which is approved by the Coast Guard (Oceana, 2013). In addition to this third party inspection system, an owner will sometimes inspect his or her own vessels on a regular basis. While personal inspection is a good practice, it is not a replacement for a third party or Coast Guard inspector who would normally be less biased (*Federal Register*, Sept. 2011). If a company opts to be inspected by a third party, the Coast Guard must approve and audit the third party inspection system as well as the company approximately every five years. If a company does not opt for a third party system, as might be the case for a smaller company without the resources of a larger company, Coast Guard officials will inspect the company’s vessels yearly. While this is the general inspection system process, towing vessels are currently not regularly inspected, and will not be until 2015.

2.1.4 Changes to Inspection System

Since towing vessels were put under USCG purview in 2004, they have been classified as uninspected vessels, and as such there have been no required, regularly scheduled inspections put in place (*Federal Register*, Aug. 2011). Up to this point, there have only been examinations of individual vessels when a particular reason came to the attention of either the owner or the Coast Guard. Recently, the Coast Guard has decided to institute a new system but wants to ensure that this new system is operating at its full potential.

2.1.4.1 New Inspection System for Towing Vessels

In order to ensure that the towing vessel industry is cooperating with this new system, the Coast Guard (Towing Vessel National Center of Expertise, 2013) has held several public meetings through the Towing Safety Advisory Committees (TSAC) where towing vessel industry representatives participate in the discussion of regulations and inspections (*Federal Register*, Sept. 2011). The Coast Guard hopes that, by including the industry from the start, a smooth transition into an efficient, systematic, and effective system will evolve. One major concern voiced by industry representatives during the public meetings was about the rationale behind the new system. Industry representatives argued that any new regulations or inspections should address real risks instead of trying to cover every aspect of tug operations in broad strokes.

The new system is still in development and few specifics have been released. There are, however, a few existing systems in place that can be looked to for potential sources of precedence, including systems currently in place for passenger vessel inspections (USCG, 2013). Additionally, towing vessels are subject to examinations when deficiencies are noticed and reported by either the owner or the Coast Guard, or if a vessel casualty takes place. There are standard forms to fill out in the event of these examinations which include provisions for checking crew certifications and licenses, machinery, lifesaving equipment, navigational systems, structural integrity, and more. These forms represent an existing inspection method which will likely be used in part as a basis for the new system.

2.2 Prevention Measures

With the broader scope of vessels and the inspection system for towing vessels now defined, it is crucial to understand how inspection data can be used to implement better prevention measures. The Coast Guard has five pillars that fall under the category of prevention including Investigation, Facilities, Inspection, Water Ways Management, and Port Security Advisory, as demonstrated in Figure 2. Our project will be concentrating on the “Inspection” pillar, highlighted in green, with future application to all five pillars. This section provides an overview of what the Coast Guard currently does in terms of prevention and what their ultimate goal is. Understanding the Coast Guard’s available resources, relevant prevention models, and risk-reduction values, specifically for inspections, is important for our goal of creating an objective prevention methodology.

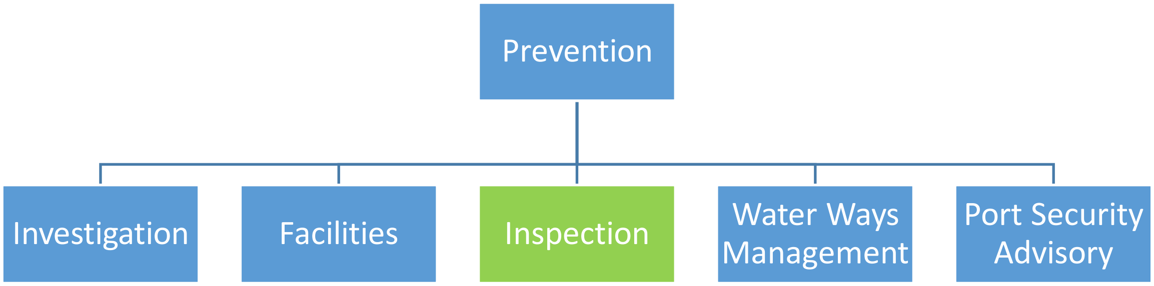

Figure 2: Prevention Pillars

Currently, the Coast Guard reports the quality of their preventative measures to Congress in terms of "tombstone parameters." These parameters include items such as deaths and injuries to crew members and passengers, vessel groundings, and collisions (USCG, 2013). These parameters, however, are not a good representation of what is done to prevent accidents from occurring. The risk-reduction measures taken during inspection systems are not accounted for when prevention data is reported, because there is currently no system for objectively looking at how deficiencies were addressed during the inspection process. Therefore, it would be useful to create a method for determining how effective inspection systems are at preventing accidents in order to allow the inspection system to reach its full potential.

2.2.1 Available Resources

At every stage of our project, we utilized a number of resources available in terms of both internal Coast Guard research, as well as external research. These resources include databases, data analysis tools, and past risk assessment models that gave us groundwork for the creation of one model tailored to vessel inspections. This section provides information on the Marine Information for Safety and Law Enforcement (MISLE) database and existing risk assessment models.

2.2.1.1 MISLE Database

Due to the wide range of responsibilities, the Coast Guard keeps extensive records of all of its activities that go back for decades. The MISLE database is the main database used at the Coast Guard (USCG, 2013). The database includes information on vessels, facilities, vessel inspections, incidents, and parties involved, keeping detailed track of all activities within the Coast Guard across all districts. This provides us with good records of deficiencies discovered during inspections, and to which system of the vessel those deficiencies pertain. We can also view the incidents that occurred each year, and access information on their financial, environmental, and human impact.

Although MISLE contains a wealth of information, it tends to be organized on a case by case basis. In order to compile large amounts of data for the purpose of analysis, the Coast Guard uses a tool called Coast Guard Business Intelligence (CGBI) that provides spreadsheets of records retrieved from the MISLE database. CGBI allows the user to filter the data by year, vessel type, and many other criteria, which proved to be helpful in our analysis of vessel data used in the creation of the risk assessment model.

From the CGBI and the MISLE database, inspection and accident data can be obtained, which proved to be the most useful data sets for designing our prevention model. Inspection reports contain information about types of systems, sub-systems, and component deficiencies. The system is the overarching classification which funnels down into a sub-system and further down, into a specific deficiency. For example, one system, “Communications,” has a sub-system, “Alarms/Indicators,” which can indicate a deficiency of the “Fire Alarm.” Thus, an inspector records these three categories of information when he or she finds a deficiency on a vessel. Accident reports provide information on the initial event type of the accident, such as a collision or fire, and the consequences of that accident, such as injuries or property damage. While our final product did not end up using information from the accident reports, they could be useful in the future to further enhance our model.

2.2.1.2 Models

Researching risk models can be useful in gaining a better understanding of how risk has previously been calculated. By looking at the ways the Coast Guard, other agencies, and other companies have already evaluated risk, a new model specific to risk-reduction due to inspections was created. General risk models, including Failure Modes and Effects Analysis (FMEA), risk indices, fault and event trees, and cost risk analysis, helped with identifying key variables and suggesting best ways to look at data (IEC/ ISO 31010, 2009-11). Specific models, such as the Maritime Security Risk Analysis Model (MSRAM) and the FMEA tool for the Institute of Health Improvement aided in providing models that are already successfully in place. Each model is explained in further depth in the following Methodology chapter. Conducting in depth research on these models was essential to creating a risk model for the Coast Guard’s prevention program.

2.2.2 Risk-Reduction Values

The Risk-Reduction Value (RRV) is a rating assigned to a vessel component based upon the potential risk the component poses to the vessel, environment, and property upon failure

(J. Buck, personal communication, October 30, 2013). It can be used to represent the amount of risk that the Coast Guard was able to prevent by finding a vessel deficiency. As our project goal is to create a method that determines the amount of risk the Coast Guard reduces by identifying and fixing issues on a vessel, the output of the method is a risk-reduction value. The Coast Guard can then use this method to help evaluate the overall performance of their inspection program.

2.3 Summary

The maritime vessel industry is highly regulated because of the risks involved in traveling by water. These risks include potential human error, as well as equipment failure and environmental risk. To ensure that the regulations are met, inspection systems are typically put in place. Towing vessels are currently not formally inspected, which allows some vessel companies to get by without meeting the regulations for towing vessels (S. Jason, personal communication, October 2, 2013). Since towing vessels are essential vessels operating in ports and harbors and potentially towing oil or hazardous material, the Coast Guard seeks to make inspections mandatory for these vessels to ensure the regulations are being upheld by each towing vessel company.

Currently, there is no method available for understanding how beneficial an inspection system is towards preventing accidents from occurring (USCG, 2013). Data is given to Congress in “tombstone parameters;” however, this does not give an accurate portrayal on what has either been done or neglected in trying to prevent vessel incidents. The Coast Guard has multiple sources of useful information that help create a system to determine inspection effectiveness.

Since the inspection system for towing vessels is currently being phased in and will be fully implemented in 2015, there is a nice spectrum of data available on towing vessels. Using this range of data and a methodology for determining deficiency values, towing vessels are a useful example in providing information on where the inspection systems were effective in preventing accidents from occurring and where improvements can be made.

Chapter 3: Methodology

Although the Coast Guard is currently instituting a new inspection program for towing vessels that, in theory, should help prevent accidents and all the costs and casualties associated with them, the program's effectiveness has no way of being tested. In order to quantitatively measure the program's performance, the USCG plans to phase in a risk-reduction rating system that would gauge the effectiveness of preventative measures based on the information about deficiencies found during inspections for all vessel types. The goal of our project is to develop a methodology for systematically acquiring risk-reduction values for various vessel deficiencies that could be utilized in this USCG model. The following sections explain the approaches and steps we took to accomplish this task.

3.1 Research of Past Performance-Measuring Models

In order to understand how risk-performance measures work, we extensively researched relevant studies and past successful models that had been applied to similar situations. This research allowed us to determine which variables and components of data analysis are most relevant to our project. Additionally, our model gains more credibility for being based on existing, trusted models. This research is presented in the following sections.

3.1.1 Risk Indices Analysis

A risk index is a quantitative measure of risk that is used as the basis for many risk management programs (USCG, 2013). Most commonly, this index is defined as a product of consequence and probability. The consequence may be measured in a number of ways, including a scaled value representing severity or scope of impact, or the direct and indirect monetary costs of the events. In a comprehensive risk index, this could include positive and negative values, potentially resulting in net positive or net negative outcomes. The probability values can either involve strict probability values ranging from 0 to 1, or more abstract values that could span any range. Any combination of these methods is valid, but each method provides the results in a different format.

One of the existing models we looked at is the Coast Guard's Maritime Security Risk Assessment Model (MSRAM), which is used to assess the risk which various potential acts of terrorism pose to ports and harbors around the country. MSRAM defines risk as a product of consequence, vulnerability, and threat. The total consequence is the sum of the outcomes of possible events. The product of vulnerability and threat provides a measure of probability and represents a calculation of the likelihood of the events in question. The end result of the MSRAM model is a risk index that represents the risk posed by any certain port or harbor.

3.1.2 Fault and Event Tree Analysis

Fault tree analysis (FTA) is used to identify the factors contributing to an accident (IEC/ ISO 31010, 2009-11). Fault trees are one method to funnel out causes of a specific deficiency or problem that occurred on a vessel. Figure 3 shows an example of a fault tree, and it illustrates the method used to analyze causational factors for an event. The event at the top of the diagram is the final outcome, and each element linked below it is a cause that directly precedes the element above it. Along the links between causal factors are symbols for logic gates, denoting if one, or all, of the factors must occur to cause the successive event to occur.

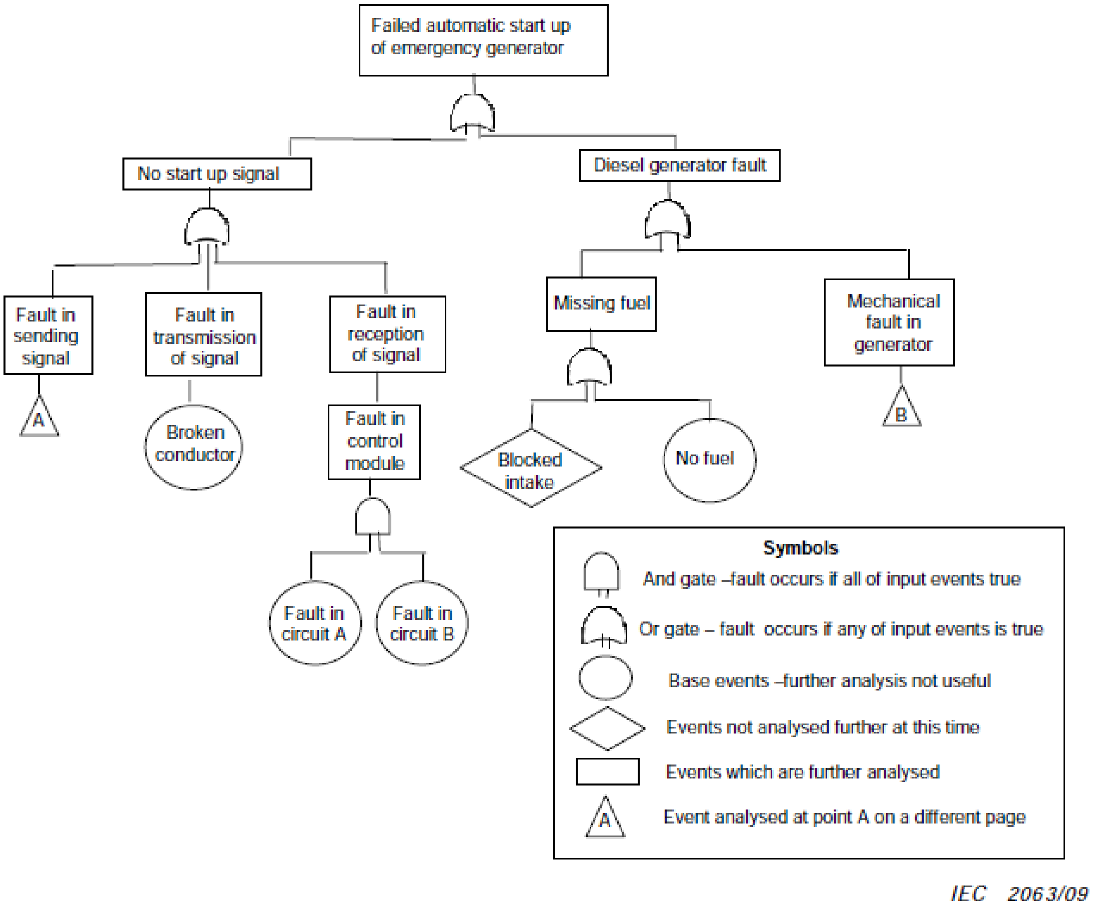

Figure 3: Fault Tree Analysis Example (IEC, 2009)

If probability or failure rate data is available, a fault tree can also be used in a quantitative manner. Fault trees allow the connection of a result to possible deficiencies that could have led to the result. Fault trees are beneficial because they can chart the way in which a deficiency would lead to a particular outcome.

A similar visual model is the event tree analysis (ETA). This model is a graphical representation of the event occurence process (IEC/ ISO 31010, 2009-11). The benefits of ETA is that it allows for multiple possible failures to be considered and analyzed sequentially. For example, as demonstrated in the diagram above, the failures in the overall system can be traced to multi-cause failures of smaller subsystems and components. Figure 4 shows how this method can be used to determine the cause of an event, in this case the failure of an emergency generator to start, and also how probabilities can be associated with the method as the basis for a quantitative analysis. On the left is the first event of the sequence, and each branch to the right represents a binary option where a subsequent event either does or does not happen, including the functioning of safety systems in place. The second-rightmost column is the outcome based on the series of events. Along the branches there are numbers which represent the probability of each option. By multiplying the probabilities of successive events, the overall probability of an outcome can be determined and, based on the frequency of the initiating event, the expected frequency of that outcome has been calculated in the rightmost column.

For example, there are 10^{-2} explosions per year, on average, shown at the left. These explosions have a chance of 0.8 to start a fire. If the fire starts, one would follow the branch up. Then, there is the sprinkler system, which has a 0.99 chance to work correctly. If it does, follow the branch up again. After that is a check for wether the “Fire Alarm” is activated, which has a 0.999 chance to occur correctly. Following that branch up leads to the outcome, “Controlled fire with alarm.” The frequency given, 7.9×10^{-3} occurances per year, is the product of 10^{-2}, 0.8, 0.99, and 0.999.

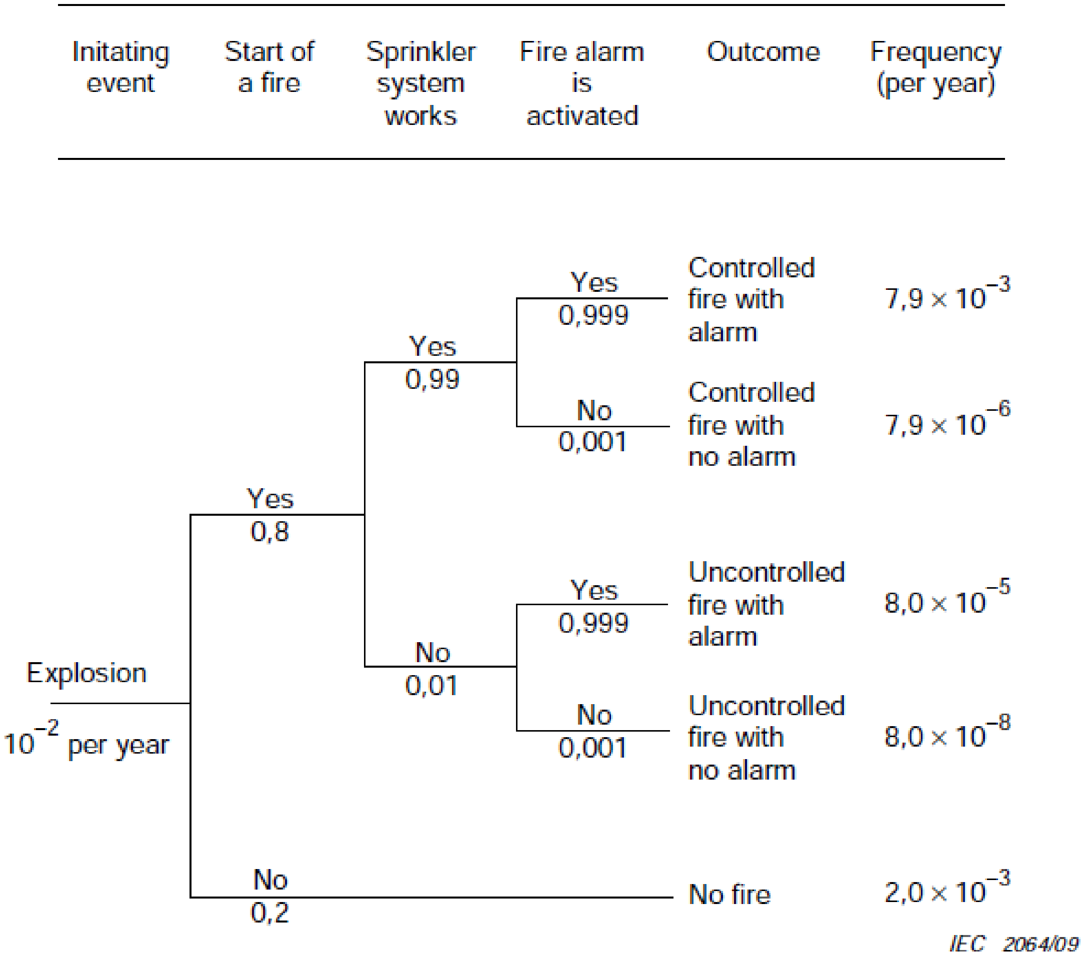

Figure 4: Event Tree Analysis Example (IEC, 2009)

By combining both the fault tree analysis and the event tree analysis, a cause-consequence analysis can be developed (IEC/ ISO 31010, 2009-11). This analysis technique gives a more complete analysis by taking the failure logic from the FTA and allowing the diagram to develop over time with the help of ETA analysis. Figure 5 shows an example diagram of how the cause-consequence analysis can be used. In this diagram, the circles at the bottom represent the base events from the FTA, which lead up through logic gates to several binary options, as seen in the ETA. These binary options represent events that may also be influenced by other fault trees, following which they either occur or not. All of these will again have probabilities assigned to them, as may the base events of the fault trees. By combining these appropriately, as in the ETA, probabilities for the final consequences are determined. Through this type of step-by-step, multi-outcome analysis, a comprehensive understanding of a certain event can be provided.

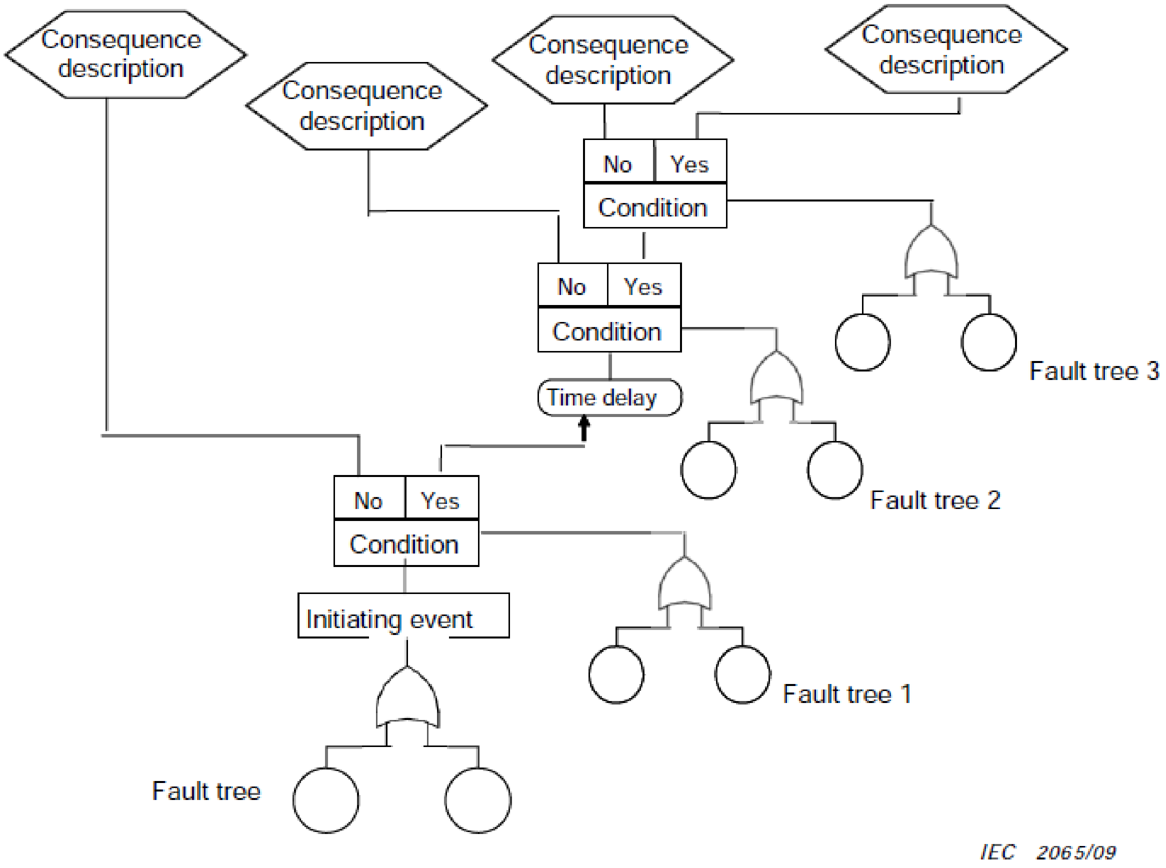

Figure 5: Cause - Consequence Analysis Example (IEC, 2009)

3.1.3 Failure Modes and Effects Analysis

The Failure Modes and Effects Analysis (FMEA) is a technique used to identify the ways a system can fail. This method focuses on prevention by aligning all potential risks with their root sources, allowing for a better approach to risk prevention. Numerically, FMEA assesses risk by assigning a Risk Priority Number (RPN) to each failure, produced by multiplying Severity (S), Occurrence (O), and Detection (D) rankings. These rankings are all based on a one to ten scale, where a lower value corresponds to a lower risk factor. The scales for these three factors are usually produced by teams of experts who subjectively assign values to various failures based on their expertise.

While the FMEA tool allows for a comprehensive analysis of extremely complex systems with multiple variables and risk factors, it has its disadvantages (Haq, Lipol, 2011). A major concern involving the standard for assigning the S, O, and D values on a scale include the cooperation and agreement of subject experts which can make the system implementation cumbersome. Additionally, the validity of the ordinal, one to ten scale is questionable, because the degree of severity may not always vary accordingly.

One application of the FMEA is through the Institute for Healthcare Improvement FMEA tool (IHI, 2013). This institute developed a computer system that allows hospitals to calculate their Risk Priority Number. The system allows for a hospital to input different scenarios and, with each scenario, a number on a one to ten scale is assigned based on the likelihood of adverse occurrence, the likelihood of detection and the severity of the issue. These three values are then multiplied to obtain an RPN. Each scenario includes the failure mode, cause, and effect in the system. As an example, a failure mode is input as the wrong diagnosis given to the patient, the cause is given as an inaccurate exam by the provider, and the effects include the assignments and orders of wrong tests, medications, and treatments. For this failure mode, the occurrence number assigned was an eight, the detection number was a three, and the severity was an eight. These numbers are then multiplied to get an RPN for this specific mode, which in this case is 192. To get the overall RPN for all failure modes in a certain section of a hospital, all of the individual risk priority numbers are summed for that section. Furthermore, the entire hospital can be given an RPN value by summing all individual RPN values.

3.1.4 Cost Risk Analysis

Another possible model we looked at is a cost risk analysis. This model is a specific incarnation of the risk index system in which a monetary value is assigned to all consequences involved and a final monetary value represents the average expected net cost of an adverse incident. When applied to our problem, the final net cost would represent how much money the Coast Guard has saved by averting the action involved by having a preventative system in place (Yoe, 2000). This will allow a casual observer to easily assess the performance of the system as the final values are costs. This would provide a relatively simple and effective way for the Coast Guard to present their performance to third parties not involved in the inspection program.

3.2 Development of a Prototype

After the completion of our research into the different types of models available to us, we selected the aspects of each that would be most relevant and useful to solving our problem. The method that we chose to use for our main equations includes elements from risk indices and FMEA. Our method is a result of careful consideration and examination of the models researched.

3.2.1 Risk Indices Analysis

Risk Indices Analysis (RIA) is one of the models that heavily contributed to the development of our own risk based analysis of performance measures. The formula that our model shares with RIA is based upon the general formula of a risk index:

$$Risk = Probability \times Consequence.$$

However, we adjusted our model to fit the data we were provided. We also chose to use several scaled values to represent different elements of the consequence, rather than using a monetary cost, as stated in 3.2.4. The scale values that we chose were based upon the standards set by the AWO’s scale for injuries, property damage, and environmental damage.

We also chose to use some parts from the MSRAM model. We mainly used this as a guideline and for ideas on how to choose possible consequence factors, such as environmental impact, economic impact and injury mentioned earlier. However, because MSRAM is security based rather than safety based, some factors used were not applicable to our model.

3.2.2 Fault and Event Tree Analysis

While fault and event trees are a useful method for thinking through the consequences of an event, it did not apply to our purposes. Because of the large number of deficiencies, it would have been cumbersome to create a tree for each deficiency. This would not have been the best use of our time, nor would it have been feasible with the information provided to us.

While this model could provide a good visual for thinking through the risk of a deficiency, there were more effective methods for us to focus on.

3.2.3 Failure Modes and Effects Analysis

Through our research and the analysis of the data available to us through the Coast Guard databases, we decided that the FMEA would serve as a good basis for our risk performance model. In fact, the FMEA appears to lie at the heart of most risk assessment models, such as IHI and MSRAM.

As has been mentioned in earlier sections, the basis of FMEA is as follows:

$$Risk = Severity * Occurence * Detection.$$

In the case of towing vessel inspections, the "Severity" factor is based on the potential consequences of a failure due to a given deficiency. Because the data currently available does not draw direct lines between incidents and deficiencies, we had to systematically rate deficiencies on several impact scales for potential consequences. Finally, "Detection" was quantified by accessing inspection reports and statistically evaluating the frequency with which a certain deficiency is found.

3.2.4 Cost Risk Analysis

When developing the RRV model, we chose not to use a cost risk analysis. There were several factors that led to this choice, including difficulty in determining and justifying certain monetary costs, as well as the maintenance the model would require over the years to ensure the monetary values remained accurate (Yoe, 2000). When using a cost-based method, we would have to determine an appropriate value of someone's life or injury. While there are standards for these values, we would still have to decide which to use and determine the scope of these approximations. For example, the projected cost may encompass just the Coast Guard’s expenses, or it may include the personal costs. Additionally, the assigned costs will also need to be justified to multiple parties. When evaluating their performance, the Coast Guard would need to have substantial proof that they are indeed saving this much money, and cost estimates are not just based on arbitrary amounts or rough estimates. Additionally, the costs and values of services and currency are constantly changing, which would require the model to be constantly updated to reflect the current cost of services. While certain agencies, such as insurance companies and law firms, maintain and update life value tables, these periodically recurrent changes would, in turn, need to be reflected in our model. This complication could be avoided by not using cost directly in our method.

3.3 Application of Vessel Data

In order to narrow the scope and ease data analysis, we initially limited our model prototype to towing vessel inspections. This particular vessel type was selected due to the circumstances surrounding the history of their regulations; after being previously uninspected, a bridging program has been phased in over the course of the past few years, meant to prepare for the final implementation of annual inspections in 2015. This provided us with a means of comparison of recent data prior to and after the implementation of inspections, accomplishing the task of measuring their effectiveness. After this initial data analysis, we saw that it was essential to assign the RRVs based on a larger set of inspection data. To do this, we calculated RRVs using the past five years of inspection data on all vessels. These set RRVs were then applied to data for towing vessels. By doing this, we were able to more accurately calculate the RRVs and portray the RRVs for towing vessels before and during the bridging program.

3.3.1 MISLE Database

MISLE is the primary database of the Coast Guard, containing records concerning all aspects of marine activity (2013). This includes inspection information relevant to our project. From the data available, we selected the FMEA model based on our research of past performance measures as well as the needs and requirements of the model in question. The FMEA model best incorporates the data from MISLE to obtain RRVs. While aspects from other models were used in this data analysis, FMEA was the core model around which we centralized our data analysis.

3.3.2 USCG CGBI

While the MISLE database acts as the primary database for the USCG (2013) and contains all of its marine information, systematically retrieving information can be difficult. Therefore, the CGBI program was used to access and download large, and filterable spreadsheets of data from multiple years. Initially, this tool allowed us to determine what data is available through the Coast Guard databases and can be utilized for our model. The CGBI then allowed us to filter data depending on certain criteria, such as vessel type and deficiency type, and became useful for obtaining the data necessary to test our prototype.

3.4 Testing of the Final Product

Once we developed the RRV model, we needed to ensure that it was working appropriately. To do so, we once again used data from the MISLE database and CGBI program. We initially looked at towing vessel data from the past five years. Specifically, the inspection reports were utilized for the purpose of measuring frequency of detection of deficiencies used in our model. We then assigned test values to different deficiencies and input the values into our model. By repeating this process for several different types and severities of deficiencies, we were able to estimate the range of values our model can produce, as well as judge whether the values produced were reasonable. For example, the risk-reduction value of a light in the crew quarters not working should not be higher than that of the electrical system malfunctioning. Finally, we applied the scale of 1-100 to the RRVs across all systems, where a 100 corresponded to the highest RRV produced.

Due to the time constraints, we only ran enough tests to ensure that the RRV model was on the right path. The model passed those tests, so we went on to present it to the Coast Guard, where subject matter experts will perform the bulk of the testing and fine tuning to make the model fully functional. These tasks will include, but will not be limited to, collecting more data and adjusting the scaling to fit the needs of the Coast Guard.

Chapter 4: Results and Analysis

4.1 Risk-Reduction Model

As stated in previous sections, the main objective of our project is to quantify the risk-reduced by deficiencies found during marine vessel inspection. To do so, the model assumes a vessel is a *sum of systems* examined during an inspection. The model uses the framework inherent in the USCG MISLE Database. MISLE includes three levels for vessels systems, the highest level is a system, then sub-systems, and the sub-systems are further broken down into components. Figure 6 displays the branching within MISLE.

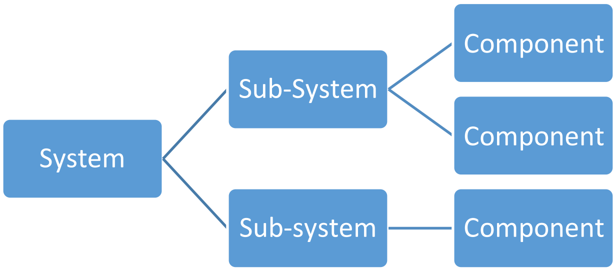

Figure 6: System Breakdown from USCG MISLE database

For example, the system "Communications" includes "Alarms/Indicators" as a sub-system. Each sub-system includes relevant components; for example, "Alarms/Indicators" contains items such as a "General Alarm" and "Fire Alarm," as illustrated in Figure 7.

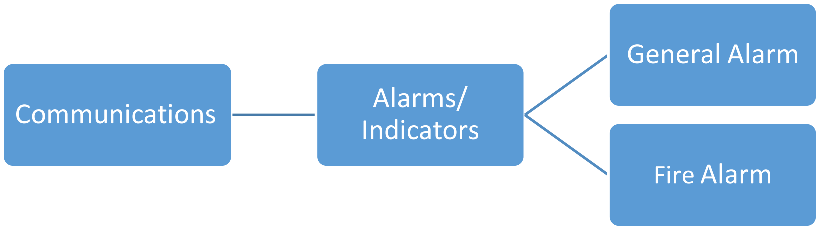

Figure 7: Example System

The lowest branch, components, connects to the deficiency found during inspections. Therefore, the U.S. Coast Guard's leaders may measure marine inspection performance in risk reduction values by summing deficiencies found during inspections.

In order to quantify the value of risk reduced, the proposed model assigns a Risk-Reduction Value (RRV) to each deficiency. However, in order to provide an accurate measure of performance, these values need to be assigned systematically throughout all systems. Relying on the research of past risk-based performance measures and keeping in mind data available to us, we based risk-reduction values on their severity and frequency, as show below in Figure 8:

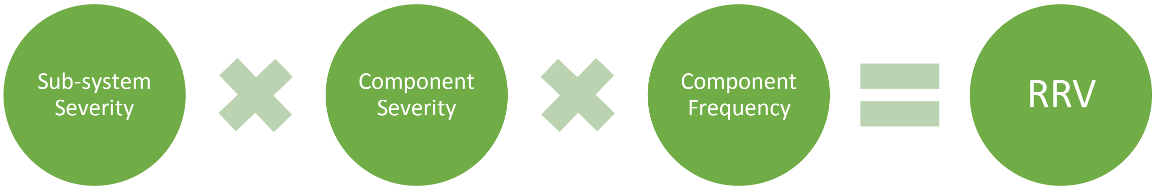

Figure 8: RRV Equation

The model assigns severity and frequency factors to the MISLE components, but only addresses severity for the sub-systems.

$$RRV = Subsystem\ Severity \times Component\ Severity\ \times Component\ Frequency.$$

Where:

$$Component\ Frequency\ =\sqrt{\frac{\#\ compoent\ deficiencies\ detected}{total\ \#\ of\ deficiencies\ found}\times 100+1}$$

The sub-systems were chosen over the larger systems for a more comprehensive analysis because they are more specific. The process and basis for calculating these are explained in the sections below.

4.1.1 Assigning Severity

The severity of sub-system failure is measured in terms of potential consequences of this failure. Three factors were used in the evaluation of severity: *human casualty, environmental impact* and *property damage*. A group of vessel inspection subject matter experts rated each sub-system concerning these factors.

Table 1: Sub-system Environmental Impact Severity Scale

No Impact	0
Minor, Small Scale Impact (<10 gal oil spilled in water)	1
	2
Moderate Impact (100 – 500 gal oil spilled in water)	3
	4
Severe, Large Scale Impact (>1000 gal oil spilled in water)	5

The model measures the factors on a 0-5 scale, with a lower value corresponding to a lower impact. However, because the RRV is a product of three numbers, a default value of one has to be assigned to at least one factor in order to prevent any one RRV from becoming reduced to a zero. Human casualty ranges from minor/no injury, up to multiple deaths; environmental impact is represented through gallons of oil spilled, ranging from zero to over

1,000 gallons; finally, property damage in dollars spans from \$0-\$50,000, to over \$250,000 at the highest end of the scale. Table 1 provides a visual of the environmental impact severity scale. Refer to Appendix E for all of the visual representations of severity scales.

Assigning severity to each sub-system demonstrates a difference between a sub-system of lesser value and a smaller impact, and one with higher importance in the event of failure. Therefore, the severity value has the potential to boost or dampen the value of any components within a given sub-system. It is essential to have multiple SMEs rate each system's components using these scales in order to obtain less subjective values.

4.1.2 Component Frequency Calculations

Every sub-system contains a number of components or potential deficiencies; these are approached similarly to the sub-systems in terms of severity, with the addition of frequency calculations. However, there are some differences in the specifics of the scales and calculations. This section will focus on frequency, which is calculated as follows and illustrated visually in Figure 9:

$$Frequency = \sqrt{\left(\frac{component\ deficiencies\ detected}{total\ deficiencies\ detected} \times 100 + 1\right)}$$

Proportion of Deficiencies Detected to Total Deficiencies Detected	• Scales values against increasing number of inspections
Multiplying by 100	• Increases the relevance of smaller frequencies
Adding 1	• Ensures every component will have minimum RRV of 1, even if the number of detections are 0
Square Root	• Reduces the impact of higher frequencies to avoid overpowering limited severity values

Figure 9: Frequency Equation Components

The figure above summarizes the components in the equation. The model divides the number of times a specific component was deficient during inspections, by the total number of deficiencies in a given time period. This function allows deficiencies across all sub-systems to be compared to one another. This results in more weight given to deficiencies with a higher probability of failure due to frequent discovery, since that is indicative of more deficiencies of the same type that need to be discovered. The model applies a square root to the frequency to dampen its effect on the final RRV and give higher priority to a component's severity rating. Finally, the value of one is a default value to deficiencies that are never discovered and consequently, lack frequency data, to ensure the RRV is never equal to zero.

4.1.3 Component: Assigning Severity

One of the three numbers comprising the RRV, component severity, was set to be measured in terms of its impact on its corresponding sub-system, or the likelihood of the failure any one component to affect a failure in the larger sub-system. The scale of one to ten was applied to this factor to allow flexibility and variation for subject matter experts during the rating process. The range of one to ten is essential toward ascertaining an accurate measure. The model averages the responses from subject matter experts to obtain a final severity value for each component. The component severity scale is provided in Table 2. On this scale, a lower value implies a lower impact. Refer to Appendix E for more details on severity scales.

Table 2: Component Severity Scale

No Likely Impact	1
	2
	3
	4
Moderate Impact	5
	6
	7
	8
	9
High Impact	10

4.1.4 Relating Sub-system and Component

Once the individual frequencies and severities are calculated for the components and the overall severities assigned for the sub-systems, they are combined through multiplication to produce a risk-reduction value for a specific component:

$$RRV = Subsystem\ Severity \times Component\ Severity\ \times Component\ Frequency.$$

A higher RRV indicates a higher risk associated with the failure of a certain component; therefore, a closer inspection of these components is encouraged to reduce the elevated risk. Through the assignment of RRVs to all deficiencies that may be issued (within MISLE), the USCG may measure the amount of RRV produced from vessel inspection. The RRV provides a conduit toward an overall performance measure for Coast Guard inspectors by quantifying the amount of risk they have reduced. Additionally, RRVs can be summed for an entire year range to compare the risk reduced through inspections annually. This allows the Coast Guard to compare their inspection performance across years, which is especially important in looking at before and after the towing vessel bridging program.

4.2 Test Case Calculation

To gain a better understanding of the process used, an example calculation for risk-reduction values will be explained in this section. This test calculation will show how risk-reduction values were calculated for the “General Alarm” component in the sub-system “Alarms/Indicators.” While our initial calculations were done using towing vessel data for the past five years, it is best to set the RRVs using a larger data set, as mentioned in previous sections. Thus, our example calculations used the past five years of all vessel data to determine the RRVs. The general equations and severity scales previously explained in section 4.1 can also be referenced in Appendix E. This section serves to give a more specific example of how our model assigns a risk reduction value to a given vessel component.

4.2.1 Sub-system Severity

The severity of “Alarms/Indicators” failing was rated on the human impact, environmental impact, and property damage scales. Subject matter experts rated the impact that “Alarms/Indicators” could potentially have on these three categories in the event of an accident based on a zero to five scale, where zero has no impact and five has the most impact.

Five subject matter experts assigned values for “Alarms/Indicators.” Their ratings were averaged for the following results:

Table 3 “Alarms/Indicators” Sub-system Impact Rating

Human Casualty	Environmental Impact	Property Damage
4.60	4.40	4.60

These individual severity values are then added to calculate the total severity value for the sub-system as follows:

$$Subsystem\ severity = 4.60 + 4.40 + 4.60 = 13.60$$

4.2.2 Component Severity

The severity value for the impact “General Alarm” has on the sub-system “Alarms/Indicators,” failing was rated on a one to ten scale by subject matter experts. The severity value for “General Alarm” was rated by five SMEs and, after averaging their responses, was determined to be 9.6.

4.2.3 Component Frequency

For each component, the frequency is calculated in terms of the total number of deficiencies detected. Deficiencies were detected for “General Alarm” 344 times in a five year period. This is then divided by the total number of deficiencies, 188,259, and multiplied by 100 to get the percentage of how often “General Alarm” deficiencies are detected out of all deficiencies. A base number of one is added to this frequency value to take into account those deficiencies not yet found. This ensures an RRV is not zero. Lastly, the square root of the frequency value is taken to ensure a non-linear growth in frequency, which allows the severity value to have a larger impact on the final RRV than frequency. The equation for “General Alarm” frequency is as follows:

$$General\ Alarm\ Frequency = \sqrt{1 + \frac{344\ general\ alarm\ deficiencies\ detected}{188{,}259\ total\ deficiencies\ detected} \times 100}$$

$$= 1.088$$

In order to demonstrate the larger impact severity has on the final RRV, an example calculation is shown in Table 4 and Table 5 below.

Table 4: Deficiency Detections Doubled

Component	Frequency	Severity	RRV (not scaled)	Change in RRV
A	1.29	6	105.29	11.10
B	1.15	6	94.19	

Table 5: Severity Doubled

Component	Frequency	Severity	RRV (not scaled)	Change in RRV
C	1.29	10	175.48	87.74
D	1.29	5	87.74	

In Table 4, the number of times a deficiency is found is doubled while severity is held constant. In this case, the change in the RRV is 11.10. However, in Table 5, frequency is held constant while severity is doubled. This time, the RRV is also doubled, and has a change of 87.74. This helps demonstrate the higher weight severity has to the overall equation and final RRV.

4.2.3 RRV Calculation

A risk-reduction value can now be calculated for each component by multiplying the sub-system severity value, the component severity value, and the component frequency value as follows:

$$General\ Alarm\ RRV = 13.60\ \times 9.6\ \times 1.088 = 141.99$$

The "General Alarm" RRV above is not normalized on a 1-100 scale. Once all RRVs are calculated, the values are divided by the highest RRV. From our initial calculations with limited severities scaled by SMEs, the "General Alarm" would scale to 81.28.

Table 6 below shows the RRVs for additional components within "Alarms/Indicators." This table serves to help compare components among each other.

Table 6: RRVs for "Alarms/Indicators"

Sub-system	Severity	Frequency	RRV	Scaled RRV (1-100)
Alarms/Indicators	13.6			
Component				
Abandon Ship Alarm	8.4	1.000531	114.30	65.43
Autopilot Alarm	4.6	1.000266	62.58	35.82
Ballast Alarm	7.6	1.001327	103.50	59.25
Bilge Alarm	9.2	1.281691	160.37	91.81
Collision Alarm	6.8	1.001327	92.60	53.01
Engine RPM Gauge/Indicator	5.8	1.066074	84.09	48.14
Engineers' Assistance-needed Alarm	8.6	1.016856	118.93	68.09
Fire Alarm	9.6	1.051778	137.32	78.61
General Alarm	9.6	1.087533	141.99	81.28
High Water Alarm	9.2	1.083618	135.58	77.62

In this table, it is evident that "Bilge Alarm" has the highest RRV, while "Autopilot Alarm" has a lower RRV. As demonstrated, our method allows for easy comparison among components' RRVs, even further simplified by the values being presented on a 1-100 scale.

Figure 10 below also aids in demonstrating the range of RRVs obtained throughout using our model.

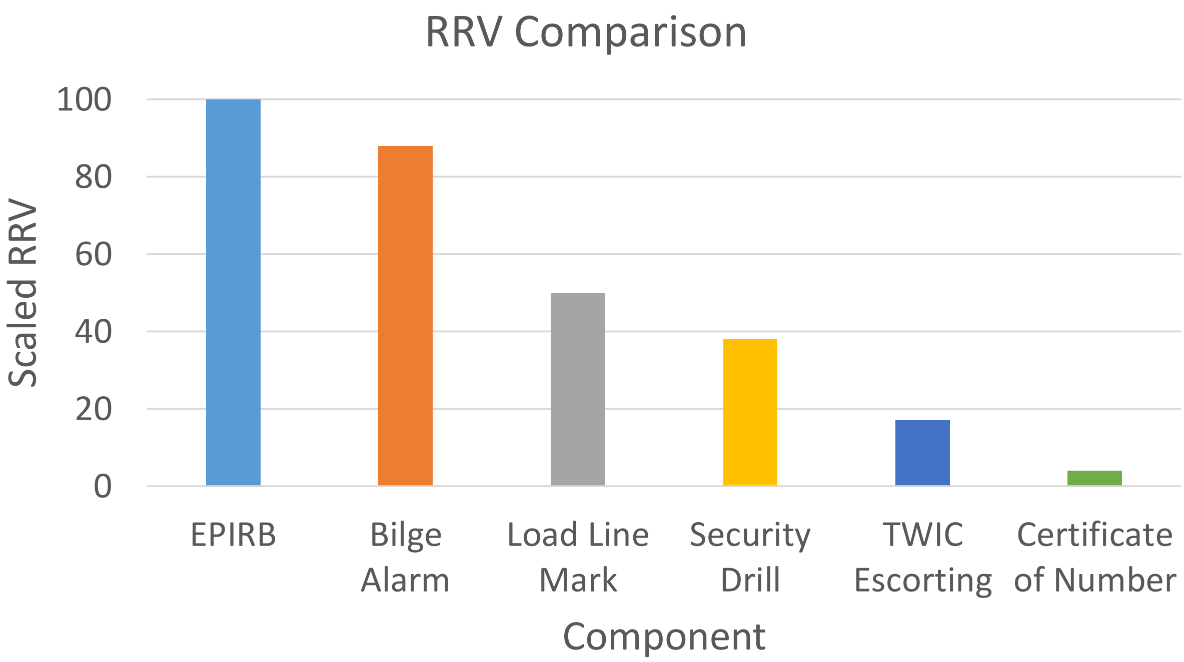

Figure 10: RRVs within Communications

This graph shows a few examples of scaled risk-reduction values. “EPIRB” has the highest RRV, scaling to a 100 with all other components normalized based on “EPIRB.” “Bilge Alarm” also has a high RRV, “Load Line Mark” and “Security Drill” have medium RRVs, and “TWIC Escorting,” “VGP,” and “Certificate of Number” have low RRVs. Thus, our model produces a range of RRVs on the 1 – 100 scale.

4.2.5 Streamlining the Process

Initially, Microsoft Excel was used to help us develop and understand the calculation process. However, using Excel to calculate the RRVs for each deficiency is a lengthy process, and involves manually creating an entry for each different component, as well as ensuring that the complicated formulas copied over correctly. With approximately 223 sub-systems and 3,000 deficiencies, a computer model was created by our team to simplify the process, streamline the calculations from sections 4.2.1, 4.2.2, and 4.2.3, and make them less reliant on user action. This model automatically pulls all of the different components from a database and calculates their RRVs. The user then needs to simply enter the severity values for each sub-system and component in order to calculate the RRV. The program also outputs the RRVs back to the database in a convenient form for future use by other applications. Refer to Appendix G and H for a user and developer guide containing more detailed information on this program.

4.3 Application of the RRV Model

The numerical assignment of risk to all deficiencies discovered during inspections opens up a variety of opportunities for its use. The RRVs can be added up for any one vessel, a geographical area, or a time period, and then compared using these criteria. The following sections discuss several examples of potential applications of the RRV model.

4.3.1 Setting the RRVs

Apart from the severity values assigned to sub-systems and deficiencies that are dependent upon subject matter experts' ratings, the RRVs incorporate frequency of detection, which fluctuates from year to year. For that reason, it is important to use a large sample of data when permanently assigning the RRVs. From our calculations, we found five years of all vessel data to be a sufficient representation of the detection frequencies; specifically, the time range between 2009 and 2013 was used. The RRVs were then normalized to a relative 1-100 scale, with the maximum value of 100 assigned to the highest deficiency value calculated.

4.3.2 Application to Towing Vessel Data

To demonstrate some of the uses of the RRV model, we applied it to towing vessel data from recent years. Due to the nature of the regulations for towing vessels, data is available prior, during, and post implementation of the bridging program that, as of 2009, includes a new requirement for annual towing vessel inspections. In combination with the RRV model, this allows for comparison between the total risk-reduction values before and after the new regulations to demonstrate how they have affected maritime safety. The chart below shows these differences.

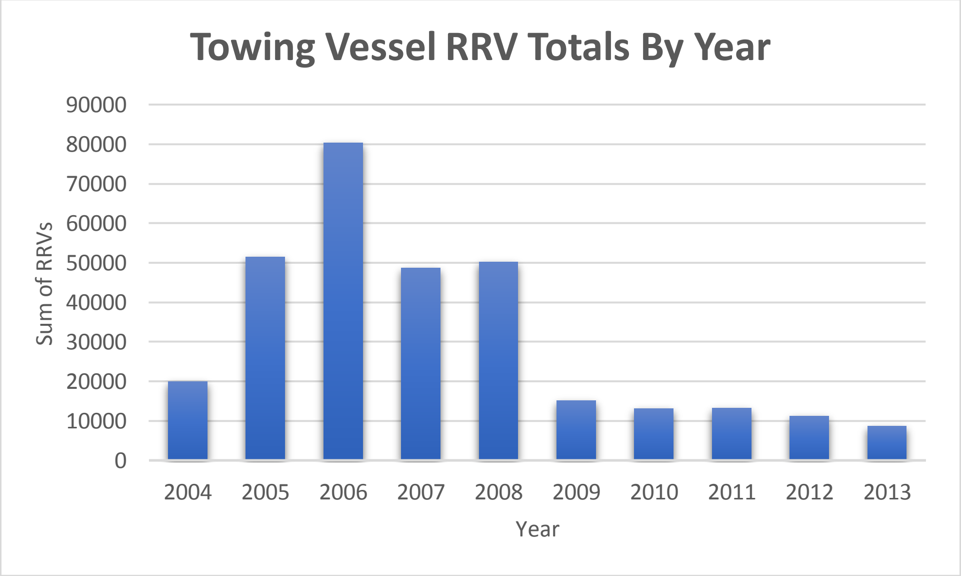

Figure 11 Towing Vessel RRV Totals by Year

Looking at Figure 11, it appears the decrease in the risk reduced per year coincided with the implementation of the new regulations in 2009. Based on the data for these years, this was caused by the drop in the number of deficiencies found annually during inspections. Although this trend has a number of explanations, it could potentially be caused by vessel owners' improved compliance with the regulations.

Another capability of the model lies in its use for calculating the average RRV per inspection each year. This can allow the Coast Guard to track trends in how much risk was reduced per vessel and correlate it with the number and extent of vessel inspections completed each year. For example, Figure 13 below utilizes the data from Figure 12, where the total risk reduced is divided by the number of inspections made in each corresponding year:

Figure 12: Number of Towing Inspections: 2009-2013

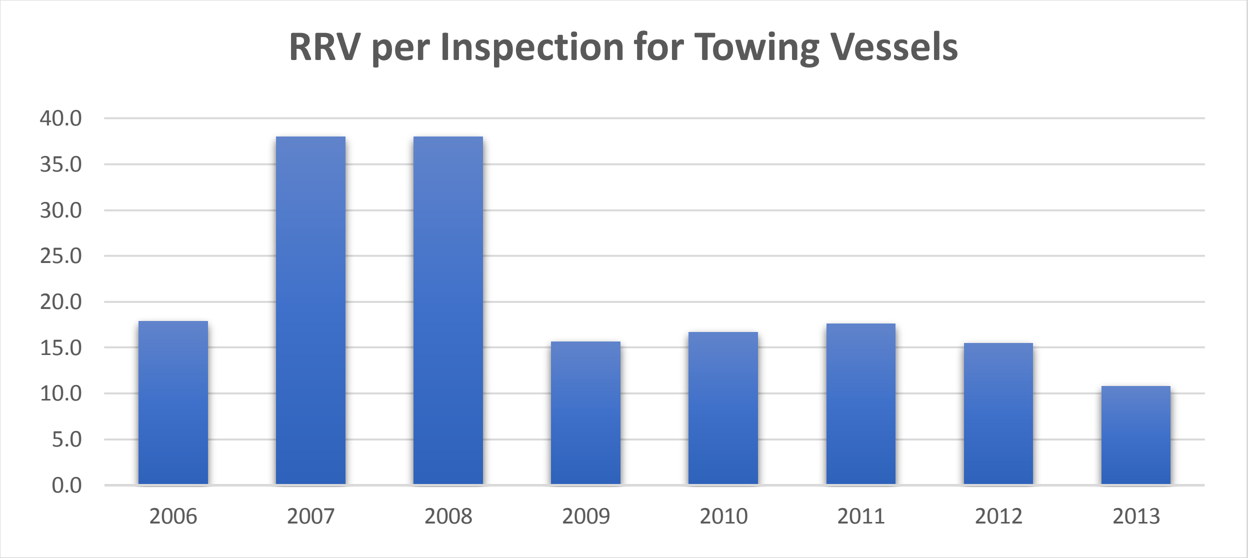

Figure 13: RRV per Inspection for Towing Vessels

Despite the large number of inspections performed in 2006, the risk reduced per inspection proved to be relatively low. This correlation may indicate that the inspections done by the Coast Guard in 2006 were not focused on in-depth examinations of all vessels, but rather, looked only at specific systems or aimed to meet a certain goal for the number of inspections for the given year. Combined with other tools and data, this type of analysis can provide insight into Coast Guard performance, allow its inspectors to better allocate their time and resources, and potentially improve the quality of inspections.

4.3.3 Identifying the Most Important Deficiencies

Currently, the Coast Guard annually reports the top ten most frequent deficiencies discovered on vessels, but solely bases their importance on their frequency of detection (J. Buck, personal communication, December 1, 2013). However, the RRV model can now allow one to gauge the value of each deficiency based on its RRV. For example, the following table provides a side-by-side comparison of two "top ten" lists of deficiencies based on these two criteria:

Table 7: Top 10 Deficiencies: 2009 - 2013

Top 10 Deficiencies: 2009 – 2013	
By Occurrence	By RRV
1. Certificate of Inspection	1. Navigation Lights
2. Oily Water Separator	2. Oily Water Separator
3. Abandon Ship Drill	3. EPIRB
4. Recovery of Survival Craft Drill/Instruction	4. Hull Plating
5. Navigation Lights	5. Fire Extinguishing System Servicing
6. Electric Generator Servicing	6. Abandon Ship Drills/Instructions
7. Bilge Water Pump	7. Electrical Generator Servicing
8. CO2 Fire Extinguishing Servicing	8. Watertight Integrity
9. Not Operational Bilge Water System	9. Recovery of Survival Craft Drills/Instructions
10. Lifebuoys Serviceability	10. Fire Doors

While there are some similarities between the components and their relative standing in the two lists, this comparison shows some important differences. Because the second column incorporates total RRV for the given year range on top of the frequency of detection, the list generated using the RRV model contains deficiencies that have comparatively larger importance. For example, the most frequent deficiency, seen in the first column, is "Certificate of Inspection," a document that poses little risk with its absence. However, the top component in the second column, "Navigation Lights," could have a much larger impact if found deficient. The inspectors can utilize this information by focusing their attention on not only frequent, but potentially most impactful components of the vessel. Finally, this new deficiency classification created with the help of the RRV model can improve the way Coast Guard assesses and reports risk-reduction and deficiency importance.

4.4 RRV's Potential Link to the Accident Data

Originally, we wanted to link component deficiencies to accident data for a consequence factor in our model. However, after talking to the Investigations Program Office (CG-INV), we determined that this is currently not feasible because MISLE does not directly link inspection and incident reports. In the future, we feel that this link could be beneficial, so the following section serves to explain how we would have calculated a value using incident reports to include in the RRV model.

The Accident Value Model focuses on ascertaining risk posed by certain accidents by evaluating past data regarding the frequency and consequences of each accident type. Frequency is universally measured in incidents per year. The consequences of the accidents are divided into three types: human, economic, and environmental. Each of these is further divided into rankings of severity which are based on an existing model created and utilized by the AWO (2013).

In the current model, data is pulled from spreadsheets produced by CGBI and filtered by Excel functions. The accident data is not pre-filtered according to vessel type, so all functions which pull data from the accident spreadsheet include a provision to compare the list against a list of towing vessels. Data on the total number of accidents is gathered, as well as figures for property damage, environmental damage, and human losses. Cells for each of these figures contain functions which filter the data according to type of accident, or collect the data from all types of accidents. All values pulled are displayed together on a separate sheet from the raw data, allowing the raw data sheets to be easily replaced with new or differently filtered data.

Most of the calculations are done by referencing the values already collected from the raw data sheets. This allows the calculation functions to be smaller and simpler. The calculations take the quantity and average data through similar processes for each subset. Frequencies are calculated by dividing the quantity by the number of years the data represent. These frequencies are then multiplied by a weight value, and then averaged per incident to provide an average resultant value. These values are then combined across the three subsets, generating the final Accident Value. Specifics regarding each subset will be discussed in the following sections, and equations showing steps in this process can be found in Appendix F. It is important to note that these calculations did not go into our final RRV model; however, we believe this could prove useful in future development.

4.4.1 Human Casualties

Human casualties are divided by the Coast Guard into four primary types: “at risk,” “injured,” “missing,” and “dead” (MISLE, USCG, 2013). In order to emphasize the importance of human life, we assigned an exponential weighting system for these. This results in “at risk” being weighted at one, “injured” at ten, “missing” at 100, and “dead” at 1000. Because of this, even if deaths are infrequent, the severity of their potential is enough to influence the overall value. The average of the weighted values is currently unaltered before being summed with the other subset values, but the model includes the option to increase or decrease the weight of human casualties in order to fine tune the system in accordance with the Coast Guard’s priorities.

4.4.2 Economic Cost

Economic costs are broken down according to the scale produced by the AWO into three ranges: <$50,000; $50,000 - $250,000; and >$250,000 (AWO, 2013). A frequency and average cost is calculated for each of these ranges and used for the calculations. The weight for each range is calculated as the number of incidents per year in that range divided by the total number of incidents per year. This weighting system ensures that more common but lower value incidents are not inherently outweighed by high-cost, infrequent incidents. The average cost for each range is multiplied by the respective weight, and then averaged. This average is compared to the original scale, and a number is assigned as the environmental factor based on the scale. If the average of the weighted values is less than $50,000 the factor is a one, between $50,000 and $250,000, the factor is a two, and over $250,000, the factor is a three. This value is added directly to the other subset values to provide the overall Accident Value, but could be weighted higher or lower in accordance with the Coast Guard's priorities.

4.4.3 Environmental Impact

Environmental impact is measured by the Coast Guard in terms of gallons of oil spilled. In the model, the severity is based again on the AWO scale, this time with ranges of less than ten gallons, 10 – 1000 gallons, and greater than 1000 gallons. The process for calculating the environmental impact subset value is nearly identical to that of economic cost, except that it uses this other scale to divide and compare the values to, with less than ten gallons representing a one, 10 – 1000 gallons as a two, and over 1000 gallons is a three. This value can also be weighted, but is currently added directly to the previous two in order to produce the total Accident Value.

Chapter 5: Conclusions and Recommendations

After eight weeks of researching, designing, and testing our model for calculating risk-reduction, we have drawn conclusions about how our model should operate and the larger impact it can have. This section also serves to explain recommendations for improvements that could be beneficial to the Coast Guard's ongoing risk assessment mission.

5.1 Conclusions

Through the use of our model, RRVs are calculated in a standardized manner. With careful research, we have created a model using previously developed methods and related them specifically to the purpose of marine inspection. Our automated program is designed to calculate and set all RRVs for USCG MISLE deficiencies, which can then be applied to calculate the risk-reduced on specific vessels, such as towing vessels. The RRV is supported by five years of deficiency data from USCG business intelligence. Additionally, our model is sustainable and has the potential for application to other types of vessels or USCG Prevention missions in the future. In summary, the model has the following positive aspects:

- Based on previously developed risk models
- Allows for easy comparison across values of different systems
- Includes large sample size to account for deficiency frequency in order to set the RRVs
- Can be applied to obtain the risk-reduced for towing vessels
- Subjective values are produced by experts
- Has potential for application within multiple USCG Prevention missions (e.g., any inspection focused mission).

While we would ideally like to include the AV within the RRV model, we believe that doing so is not currently feasible. After speaking with the Investigations Program Office (CG-INV) at USCG HQ, it was decided that accidents and deficiencies cannot be directly connected to the RRV due to a lack of supporting data. Additionally, accidents rarely directly correlated with component failures, and instead are often caused by human error. While there is a possible connection between deficiencies and accidents that could potentially be beneficial in the future, it would be detrimental to our model to include them in our final product at this time.

The calculated RRVs will then be applied to a larger program that will determine the overall performance of inspections. This overall performance will include the accomplishment of inspections along with the cost of doing an inspection. Thus, having a standardized system to measure the risk-reduced due to an inspection aids in calculating the overall performance of inspections.

5.1.1 Application of the RRV Model to Towing Vessel Data

Because towing vessels were previously uninspected, three sets of inspection data will soon exist for this type of vessel. Those will include deficiencies found prior to regular inspections, during the bridging program, which came into effect in 2009, and eventually, post-implementation of the new regulations. The RRV model can then be used to calculate risk reduced during each time period, and allow the Coast Guard to determine the value of the changes made to towing vessel regulations. This can be accomplished by adding up all the risk-reduction values for any given time period and comparing with the sum of the values for another time period. Finally, the RRV model can also demonstrate trends in deficiency severities and frequencies prior and post the implementation of these new regulations, as seen in Figure 11 from the Results chapter.

5.2 Recommendations

During the process of developing the RRV model, we realized that several aspects could be improved upon, but doing so was out of the scope of our project. While these are not necessary to use with our model, we recommend that they be taken into consideration in potential future iterations. These could not only improve the usability of our model, but also other applications of our model and other projects. These recommendations for improvement are outlined below.

5.2.1 Improve Data Quality

While there is a wealth of data in the MISLE database that could potentially be useful, a lot of it cannot be utilized for our immediate purposes due to the way the database is organized. For example, some fields that should be numeric are stored as text values instead of as numerical values, making it necessary to convert these values before performing any operations. Along with type mismatch, a lot of fields that could easily be represented by a set of predefined, scaled values, such as accident causes, are simply entered as text values. This creates potential for a lot of human error associated with spelling of the accident types, which could interfere with sorting the data later on and unnecessarily complicate numerical data analysis. Trying to analyze data that is not entered in a uniform format requires extensive, and perhaps excessive, human input and interpretation. Such issues could be resolved by using numerical coding, and, where possible, scaled data fields instead of text fields. Use of predefined quantifiable entries for fields such as accident category would greatly improve the usability of that data in terms of quantifiable analysis.

5.2.2 Link between Accidents and Deficiencies

When we first envisioned our model, we wanted to base the severity of a deficiency on the types of accidents that it could cause. However this was not possible because there are no direct links between deficiencies found during inspections and causes of accidents. While we understand that not all accidents are caused by deficiencies and it is difficult to determine if a deficiency did actually cause an accident to occur, a potential link between an incident and deficiencies noted in the most recent vessel inspection would add a more quantitative consequence to the model. However, this link would have to be discussed and confirmed with the subject matter experts on incident investigation before making recommendations and implementing this strategy into our overall method.

5.2.3 Verifying Consequence Scale

When creating the consequence scale for the failure of any given system, we decided to base the scale on the AWO’s scale for gauging the severity of impact of each factor when an incident occurs. These factors include human injury/death, environmental impact, and cost of damages. While we believe that the AWO scale was a good basis for this purpose, we are unsure about how well it aligns to the Coast Guard’s internal measures of accident severity. We recommend an assessment be undertaken of the extent to which the two align with one another. Additionally, the weight of each severity factor within the model can be adjusted in accordance with Coast Guard’s goals. For example, while human, environmental and financial impact components are currently weighed equally on a 0-5 scale, the human injury and death factor may be adjusted to carry more weight than the other two factors to produce more accurate RRVs.

5.2.4 Component Scale Clarifications

After we sent out the deficiency lists to several subject matter experts, we often found their ratings largely inconsistent. While we understand that some inconsistency is inevitable, we expected a smaller standard deviation among different SMEs. This may be due to the differences between the deficiencies on inspection sheets from those in the MISLE. Additionally, we received some feedback concerning creating description for some components, as some tend to be unclear. We believe this might aid in decreasing the standard deviation and creating more accurate RRVs. Finally, we also recommend that a large amount of SMEs to rate the components using our scales for more accurate and less subjective severity values.

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Appendices

Appendix A: Sponsor Description

The United States Coast Guard (USCG) (2013), established in 1790, is a non-profit government organization and a branch of the U.S. Department of Homeland Security during peace time and United States Navy during war. Their mission is: "We protect the maritime economy and the environment, we defend our maritime borders, and we save those in peril" (Missions). Under this, there are 11 sub-missions of the USCG including:

1. Ports, waterways, and coastal security
2. Drug interdiction
3. Aid to navigation
4. Search and rescue
5. Living marine resources
6. Marine safety
7. Defense readiness
8. Migrant interdiction
9. Marine environmental protection
10. Ice operations
11. Other law enforcement

In order to fulfill these missions, the USCG has access to a large number of resources. The USCG is funded by the United States Government with a budget for the 2014 fiscal year of $9.79 billion. In 2012, the USCG had over 43,000 members on active duty, 8,000 reserves, and over 8,800 civilian employees.

The USCG (2013) is led by a Commandant, Admiral Robert J. Papp, Jr., and Vice Commandant, Vice Admiral John P. Currier. Under them there are two deputy commandants, one in charge of operations and the other in mission support. The operations department includes capability and marine safety, security, and stewardship, while mission support covers a host of units which includes Command, Control, Communications and Information Technology (CCC and IT), Human Resources (HR), Force Readiness Command (FORCECOM), and Logistics (See Figure 12). The USCG is divided into two geographical areas, Atlantic and Pacific, each with its own commander. These areas are further divided into 9 districts as seen in the map below.

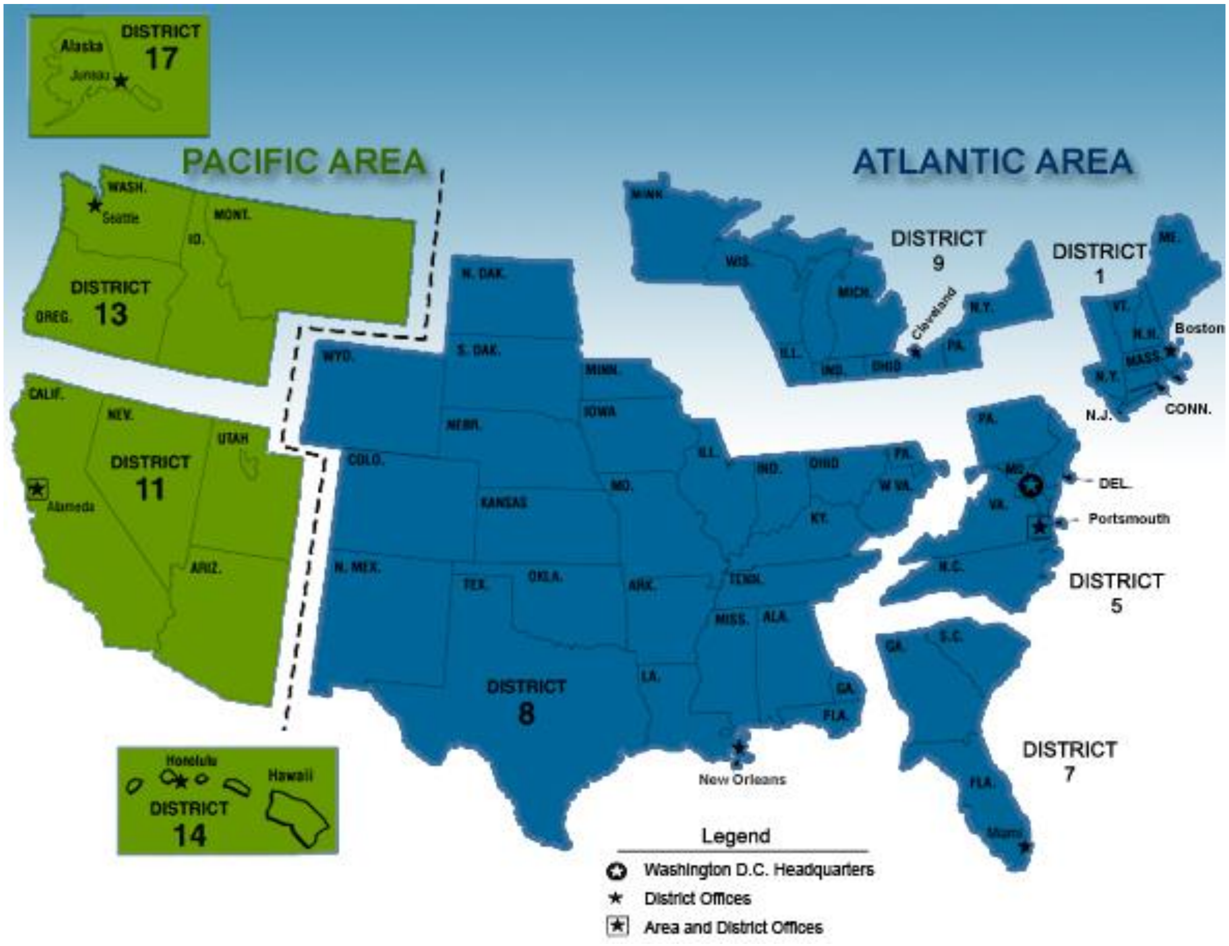


Figure 12: USCG District Map (Units, 2013)

CG-5 is one of ten major groups within the USCG (2013) and denotes the department for Marine Safety, Security, and Stewardship. The office that is especially relevant for this project is the Office of Vessel Activities, which is part of this department. The mission of this unit is to ensure that all vessels in U.S. waters are up to the USCG standards through vessel safety and inspection programs. The office also enforces international treaties and domestic regulations. The full organization of the USCG can be seen in Figure 13 below.

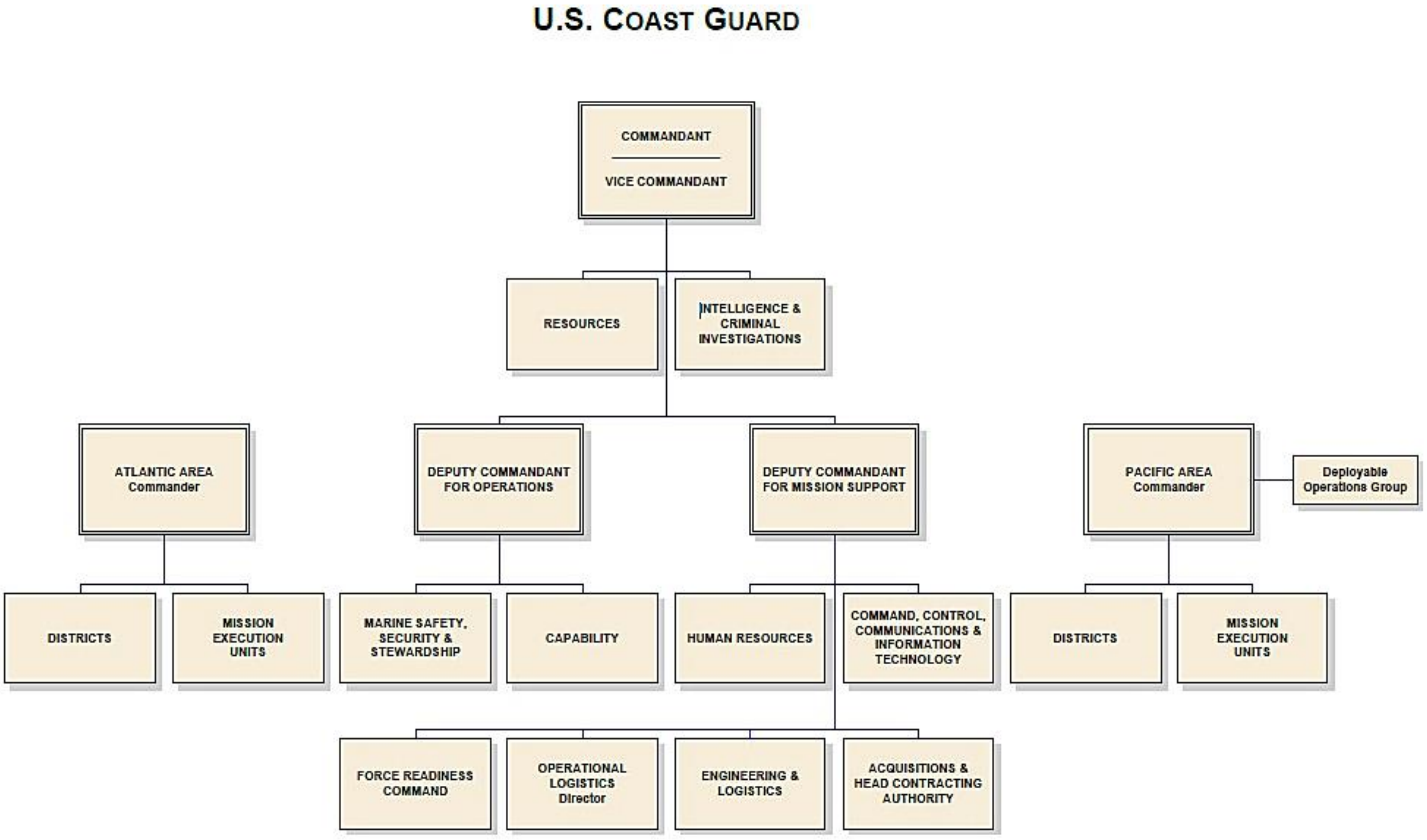


Figure 13: USCG Organizational Chart (Organizational Structure, 2013)

To reach their safety goal, the Office of Vessel Activities is seeking to improve their current vessel inspection program. Helping to achieve this goal, the USCG (2013) has partnered with several organizations including American Waterways Operators and The International Association of Independent Tanker Owners. Through the American Waterways Operators partnership, they have achieved safer operations during dangerous water conditions and dealt with safety concerns with crew fatalities and tank barge spills. The International Association of Independent Tanker Owners has helped facilitate better communication with the USCG and the vessel industry while aiding vessel safety.

Appendix B: What is an IQP?

The purpose of an Interactive Qualifying Project (IQP) is for students at WPI to gain a "broad understanding of the cultural and social contexts of those fields, and thus be more effective and socially responsible practitioners and citizens" (WPI, 2013, Interactive Qualifying Project). The IQP experience is unique because it is not a typical course setting, and it is not directly related to a student's major. Rather, it combines the technological and social aspects of society to allow students to work beyond their technical backgrounds. To accomplish this goal, "small teams of students work under the guidance of faculty members from all disciplines to conduct research, using social science methods, directed at a specific problem or need" (Interactive Qualifying Project). Typically, project sponsors are nonprofit, municipal, or government agencies. An IQP fosters team skills, leadership, and the ability for students to "deliver findings and recommendations through formal reports and oral presentations to project sponsors and faculty advisors" (Interactive Qualifying Project).

Our project, Risk-Based Marine Inspection Performance Measures for USCG Prevention Program, qualifies as an IQP by allowing us to help solve a problem our society faces. Directly, this project aids the Coast Guard in evaluating their performance, but it plays a part in a larger context. By helping the Coast Guard in their maritime safety mission, it will impact society by improving the safety of vessels travelling in U.S. waters, and as a result make U.S. waterways safer for everyone. Additionally, our project allows for interdisciplinary collaboration by having a team of two chemical engineering majors, a computer science major, and a civil engineering major. We will touch upon the technical side through our research on risk assessment, and incorporate the societal aspects of how to measure preventative performance. With this collaboration and with working on a major societal issue, our project is considered an Interactive Qualifying Project.

Appendix C: Interview Protocols

Towing Vessel Company Representatives:

1. What, generally, is the towing industry like?
2. How many towing vessels does your company own?
3. How many towing vessels does the average company own?
4. What is the usual geographic range of work for a company?
5. What kind of work is most common? Emergency towing or scheduled movement of larger ships?
6. What kind of towing work does your company do, primarily?
7. Where do most of the safety regulations followed by your company come from? Company policies, Coast Guard regulations, or third party standards?
8. In your opinion, which regulations have been most effective in keeping the industry safe? Why?
9. How transparent has the Coast Guard been about their upcoming inspection and regulation system?
10. What kinds of hazards is your company most concerned with when operating towing vessels?
11. Does your company believe that more regulations would lead to safer vessels and vessel operation? Why or why not?
12. Do you notice that some companies are less stringent in following industry safety standards? If so, why do you believe this is the case?

Appendix D: Interview Transcripts

D-1 Foss Maritime Company

October 2, 2013
Scott Jason, Project Manager, Atlantic Division
617-561-0223
Interviewers: Christina Bailey, Erika Kirichenko
Recorder: Mitchell Caisse
Medium: Telephone

1) What is the towing industry like? What is the average size of a company and what kind of work is most common?
    a. Towing vessels aid all container ships that are coming into port.
    b. Petroleum is the biggest job performed by towing vessels in the North East. In Massachusetts 50% of all gasoline is transferred by barges being maneuvered by towing vessels.
    c. Industry has a very high barrier to entry, with the cost of tug boats and meeting industry standards.
        i. Not many small operators are currently entering the industry.
2) How has the towing industry changed in the past few years?
    a. Towing vessels are becoming more specialized in their roles in the past 10 – 15 years.
    b. Harbor assist tug boats are being build specify for maneuvering large ships, have multi directional thrust, and large amounts of horse power.
        i. This has greatly increased the safety of harbor assist, as the towing vessels can now move in every direction rather than just forward and backwards.
    c. Integrated Tug and Barge (ITB) reduce the risk involved with towing barges, as instead of using lines to pull the barge, the tug boat attaches directly to the barge and it acts as one ship.
    d. New winches that handle the lines and perform automatic line recovery for lost lines, taking away the crew’s responsibility for manipulating the lines.
    e. Advancements are limited to large companies that have the capital for newer technologies as well as the need for safer vessels, mostly companies working with high value cargo (ex. petroleum, wind mill blades, drilling equipment.)
3) What types of accidents are most common and what can be done to help reduce them?
    a. Human error, every incident comes down to some form of human error, either because the captain turned the wrong direction or the ship was not properly maintained.

    b. Crew endurance management and proper rest are the most important but also the most difficult to properly implement and enforce.

4) How many people on average are on a towing vessel?
    a. Varies depending on the location of the vessel and the work it is performing
        i. Harbor Assist vessels have 2 operators, a deck hand and a captain
        ii. Ocean going ITB have 9 operators on board.
5) How is your company currently regulated?
    a. Regulated by third parties, insurance companies and international standards.
    b. USCG also over sees regulations, but Foss maintains a higher level of regulation than current USCG standards.
6) How transparent has the Coast Guard been about their upcoming inspection and regulation system?
    a. They have been very transparent with towing vessel operations who report their safety operations to them.
    b. They have press releases, a bridging program, and companies can volunteer to have their vessels inspected by USCG.
7) What kind of hazards is your company most concerned with when operating towing vessels?
    a. Physical injury of deck hands, no one wants to see their crew to get hurt.
    b. Having a towing vessel get stranded, as the USCG does not have the equipment necessary to tow a towing vessel.
8) Does your company believe that more regulations would lead to safer vessels and vessel operation?
    a. The current issue is not with lack of regulation but the lack of enforcement, if the currently industry standard regulations are enforced, then that should lead to safer vessels.
    b. The regulations will have to be enforced equally across all companies. Unenforced regulations disadvantages to companies that do follow the regulations.
    c. Unsure how thorough the USCG can be in inspection with their limited budget and resources.
9) Where do most of the safety regulations followed by your company come from? Company policies, Coast Guard regulations, or third party standards?
    a. States set laws / regulations to enforce safety standards
        i. California has one of the highest standards to operate vessels. Need certain type of vessel to assist certain ships.
    b. American Bureau of Shipping (ABS) does USCG inspection on barges and bigger vessels.
    c. Beyond class society ships there needs to be skilled inspectors.
    d. All of Foss's vessels are International Safety Management Code (ISM) certified by International Maritime Organization to prepare for USCG standards.

10) How do you feel more regulations will affect the industry?
    a. It will make it harder for smaller companies to enter the industry and stay in the industry.
    b. Majority of the bigger companies already follow industry standards, not much change to them.

D-2 McAllister Towing of Narragansett Bay

October 2, 2013
Captain Gary Oliveira, Vice President and General Manager
401-331-1930
Interviewers: Christina Bailey, Nick Smith
Recorder: Mitchell Caisse
Medium: Telephone

1) What is the towing industry like? What is the average size of a company and what kind of work is most common?
    a. The size of a company depends on where the company is located and what kind of work that they are doing. The number of vessels a company has can vary from 1 to 100.
    b. McAllister has about 9 towing vessels and mostly focuses on emergency towing, assisting ships in ports / harbors, and towing barges.
    c. They operate in 13 ports on the east coast of the U.S. from Maine all the way down to Puerto Rico, and have 3 locations in Massachusetts alone.
2) Where do most of the safety regulations followed by your company come from? Company standards, Cost Guards regulations, or third part standards?
    a. Each company defines their own standards, as well as follows standards setup by other organizations which include American Waterways Operators (AWO), the United States Cost Guard (USCG) and Oceana.
3) How transparent has the USCG been about their upcoming inspection and regulation system?
    a. The information that the USCG releases depends on the company
    b. McAllister is involved with joint training with the USCG as well as most other companies in the industry
4) What changes do you expect to happen when the USCG's new regulations are put in place?
    a. It has been in the works for about 10 years and bigger companies in the industry have been preparing for it and self-regulate, not that much of a change when they are put in place.
    b. USCG regulations will follow the regulations that are already industry standards.

5) What kind of hazards is your company most concerned with when operating towing vessels?
    a. Bad weather, equipment failure, moving heavy gear around on deck.
    b. Implemented safety standards to reduce the safety risk associated with these.
6) Does your company believe that more regulations would lead to safer vessels and vessel operations?
    a. No, the current regulations that are in place are sufficient, they just need to be enforced properly.
    b. Currently only larger companies follow the industry regulations, allowing smaller towing companies, which usually do not follow the industry regulations, to outbid bigger companies.
7) What are some of the ways to lower the amount of human error that occurs?
    a. Training crew members properly for the work that they will be doing and having routine drills and exercises to ensure crew members know how to respond in an emergency situation.
    b. Smaller companies tend not to train their crew as well, pay them less, and have less safety equipment on board.
8) What are the most common accidents and what usually causes them?
    a. Injuries to crew members and property damage
    b. Normally caused by crew members slipping and falling, or getting caught in a towing line. As well as a lack of training and/or experience.
    c. Equipment failure also occurs, but less commonly than human error.
    d. To prevent equipment failure companies have Quality of Safety Management systems and perform regular maintenance on their vessels to ensure that they are in operable order.
9) What is considered a “smaller company?”
    a. Companies that only own a few towing vessels and or a few construction barges.

Appendix E: Calculating Risk-Reduction Value

Sub-system Calculations:

$$\begin{aligned} Sub - system\ Severity &= Human\ Casualty\ value + Environmental\ Impact\ Value \\ &\quad + Property\ Damage\ Value \end{aligned}$$

Sub-system Severity Scale:

Human Casualty Scale is a measure of the likely human casualty during an accident because of the sub-system not performing as it should. The severity can be based on injury level and/or deaths, or equivalent measures.

No Impact	0
Minor to Moderate Injury (no professional medical treatment required)	1
	2
Severe Injury, Possible Death	3
	4
Severe Casualty, Multiple Deaths	5

Figure 14: Human Casualty Scale

Environmental Impact Scale is a measure of the likely environmental impact during an accident because of the sub-system not performing as it should. The impact can be measured as a quantity of oil spilled or equivalent environmental damage.

No Impact	0
Minor, Small Scale Impact (<10 gal oil spilled in water)	1
	2
Moderate Impact (100 – 500 gal oil spilled in water)	3
	4
Severe, Large Scale Impact (>1000 gal oil spilled in water)	5

Figure 15: Environmental Impact Scale

Property Damage Scale is a measure of the likely cost of property damage due to an accident because of the sub-system not performing as it should. The damage can be quantified by cost of property damaged, cost to repair, or a combination of factors.

No Impact	0
Minor Damage (<$50,000)	1
	2
Moderate Damage ($100,000 - $200,000)	3
	4
Severe Damage (>$250,000)	5

Figure 16: Property Damage Scale

<u>Component Calculations:</u>

$$Frequency = \sqrt{\left(\frac{component\ deficiencies\ detected}{total\ deficiencies\ detected} \times 100 + 1\right)}$$

$$Component\ Severity = Impact\ on\ sub - system\ (Rated\ on\ scale\ below)$$

<u>Component Severity Scale:</u>

Component Impact is defined as the components potential to cause failure <u>to the sub-system</u>. The scale below shows example values ranging from 0 to 10 based on the likely severity of failure of the sub-system containing that component.

No Likely Impact	1
	2
	3
	4
Moderate Impact	5
	6
	7
	8
	9
High Impact	10

Figure 17: Component Impact Scale

RRV Calculation:

$$\begin{aligned} &Risk\ Reduction\ Value \\ &\quad = Subsystem\ Severity\ \times Component\ Severity\ \times Component\ Frequency \end{aligned}$$

Example Severity Scale sent to SMEs:

System: Communications

Table 8: Example Severity Scale to SMEs

Sub-system		Human Casualty (1-5)	Environmental Impact (1-5)	Property Damage (1-5)
	Alarms/ Indicators			
Components		**Impact Value (1-10)**		
	Abandon Ship Alarm			
	Autopilot Alarm			
	Ballast Alarm			
	Bilge Alarm			
	Collision Alarm			
	Engine RPM Gauge/Indicator			
	Engineers' Assistance-needed Alarm			
	Fire Alarm			
	General Alarm			

Appendix F: Calculating Accident Value

Table 9, filled with 5 years of hypothetical data, shows the first step in calculating the Accident Value, which involves gathering necessary data from spreadsheets obtained through CGBI. The values shown are fairly straightforward. For property damage and environmental damage, there are number of incidents which fall into the ranges displayed, and the average value within each range. The center column contains the number of each type of human casualty for the set of data. These numbers are used in a separate table to calculate the Accident Value.

Table 9: AV Severity Scale Components

Number of Incidents	5530			
Property Damage ($)		**Human Casualty**	**Environmental Impact (gal oil spilled)**	
Count		**Total Persons Dead**	**Count**	
<$50000	5000	0	<10 gal	4600
$50001 - $250000	380	**Total Persons Missing**	11 - 1000 gal	900
>$250000	150	1	>1000 gal	30
Average		**Total Persons Injured**	**Average**	
<$50000	3200	7	<10 gal	3
$50001 - $250000	110000	**Total Persons at Risk**	11 - 1000 gal	90
>$250000	4030000	120	>1000 gal	20500

After the data is collected from the raw spreadsheets, it goes through several steps in order to generate the final Accident Value, as shown in Table 10. Each of the three subsets of consequence are separated and run through separate, but similar calculations. Human casualties have the simplest calculations. The incidents per year are multiplied by the assigned weight to produce the weighted values.

$$Weighted\ Value = Incidents\ Per\ Year_{Range} \times Weight$$

The sum of these weighted values is divided by the total incidents per year to generate the result, which in the example is 2.3.

$$Result = \sum Weighted\,Value\ /Incidents\ Per\ Year_{Total}$$

Property damage and environmental impact both have the same calculation steps, the only difference being the numbers entered and the ranges used to divide them. The incidents per year for each range are calculated as is the total, just as in human casualties. The weights, however, are calculated instead of assigned. The weights are the proportion of incidents per year of that range.

$$Weight = Incidents\ Per\ Year_{Range}/Incidents\ Per\ Year_{Total}$$

This is done in order to balance out the effect of infrequent, high-impact incidents which would otherwise dominate the overall value. This weight is then multiplied by the average value for its respective range, resulting in the weighted values.

$$Weighted\,Value = Weight \times Average\ Value$$

These values are added together to produce a total, which is then compared back to the scale originally used to separate the incidents and the subset is assigned a value from 1 to 3 accordingly. If the value falls in the low range, it is assigned a 1, in the middle range a 2, or in the high range a 3. In the example table, both total weighted values fall in the middle range, meaning both are assigned results of 2. The Accident Value (AV) is the sum of the three results which, for the example data, is 6.3.

$$AV = Result_{Human\ Casualty} + Result_{Property\ Damage} + Result_{Environmental\ Impact}$$

This value on its own bears little meaning, as there is technically no maximum value within this model; however it will provide a single, quantitative method to compare the average severity of types of accidents.

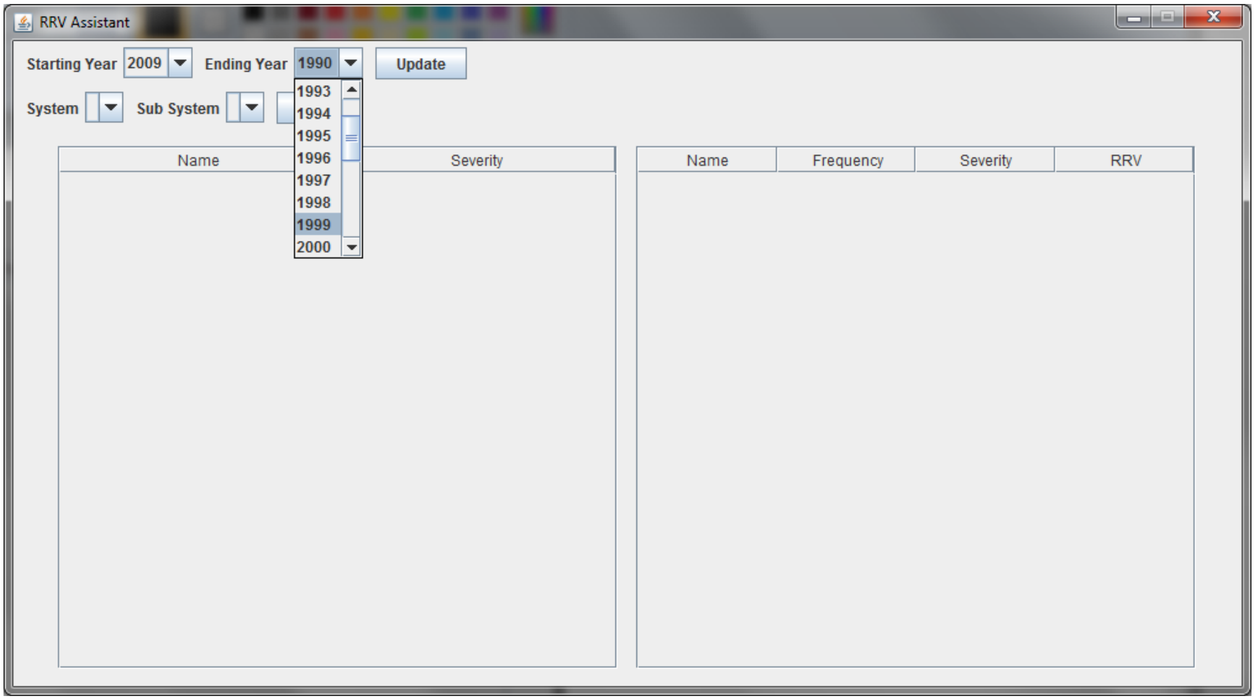
Table 10: AV Example Calculation

Accident Type:	All	**Total Incidents:**	5530	**Vessel Type:**	Towing	
Human Casualty:		**Incidents Per Year**	**Weight**		**Weighted Value**	
Death	0	0	1000		0	
Missing Person	1	0.2	100		20	
Injury	7	1.4	10		14	
At Risk	120	24	1		24	**Result**
	Total:	25.6		**Total:**	58	2.3
Property Damage ($)		**Incidents Per Year**	**Weight (inc./yr./total)**	**Avg. Property Damage**	**Weighted Value**	
0 - 50,000	5000	1000	0.90	3200	2880	
50,001-250,000	380	76	0.07	110000	7700	
250,001 or more	150	30	0.03	4030000	120900	**Result**
	Total:	1106		**Total:**	131480	2
Environmental Impact (gal. oil spilled)		**Incidents Per Year**	**Weight (inc./yr./total)**	**Avg. Env. Damage**	**Weighted Value**	
0-10 gallons spilled	4600	920	0.83	3	2.49	
11-1000 gallons spilled	900	180	0.16	90	14.4	
1,001 or more gallons spilled	30	6	0.01	20500	205	**Result**
	Total:	1106		**Total:**	221.89	2
					Accident Value:	6.3

Appendix G: RRV Assistant User Guide

The RRV Assistant makes it easier to calculate the RRV for a set of systems. Once the list of deficiencies is imported into the database and the lists of components are in the database, all that the user needs to do to calculate the RRV is to enter the severity values for the components and sub systems.

Once the application is started, the process to start creating RRVs is quite simple. First select the year range from the combo boxes labeled “Starting Year” and “Ending Year,” as seen in Figure 18 below. This range is inclusive and will determine which years data is pulled from. For example, if you were to select 2008 for the starting year and 2011 for the ending year, it will include all deficiencies found in the years 2008, 2009, 2010, and 2011.

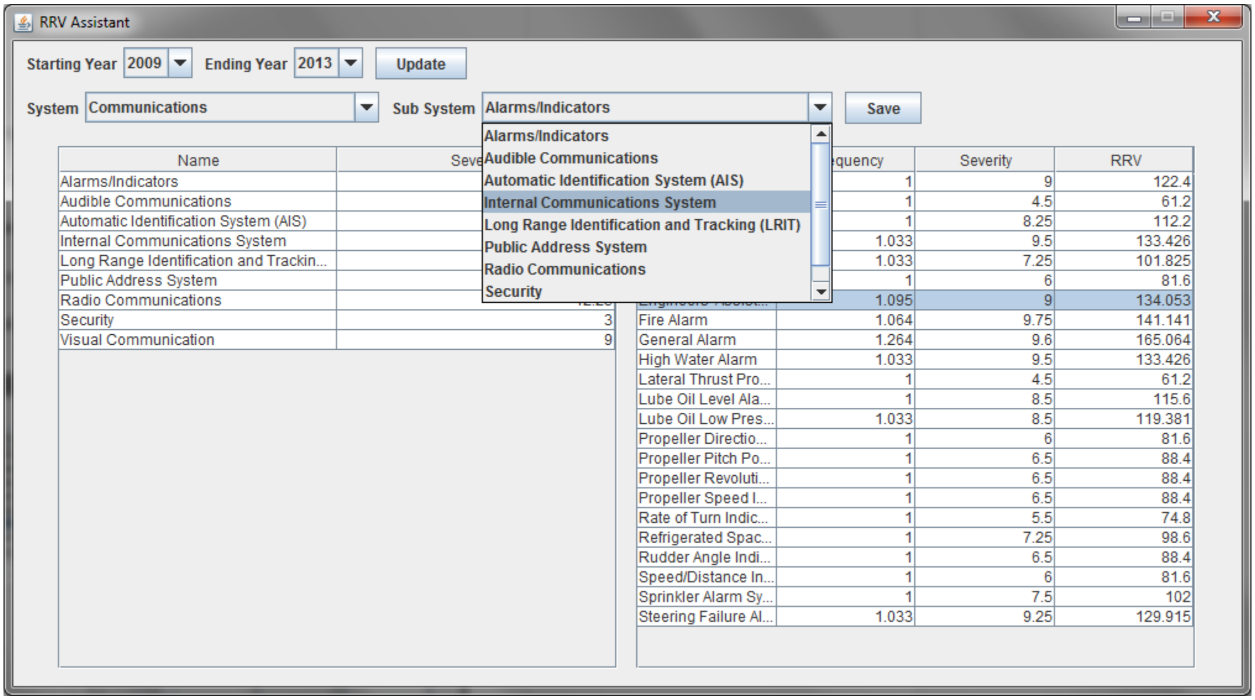


Starting Year 2009

Ending Year 1990

Figure 18: RRV Ending Year dropdown example

After the year range is selected, press the “Update” button to retrieve data about all of the components and their respective system and sub system. The systems and sub systems will populate the combo boxes labeled “System” and “Sub System” respectively. The tables below will also be populated with a list of sub systems that exists in the selected system, as well as the list of components that exist in the selected sub system, as seen below in Figure 19.



Starting Year 2009 Ending Year 2013

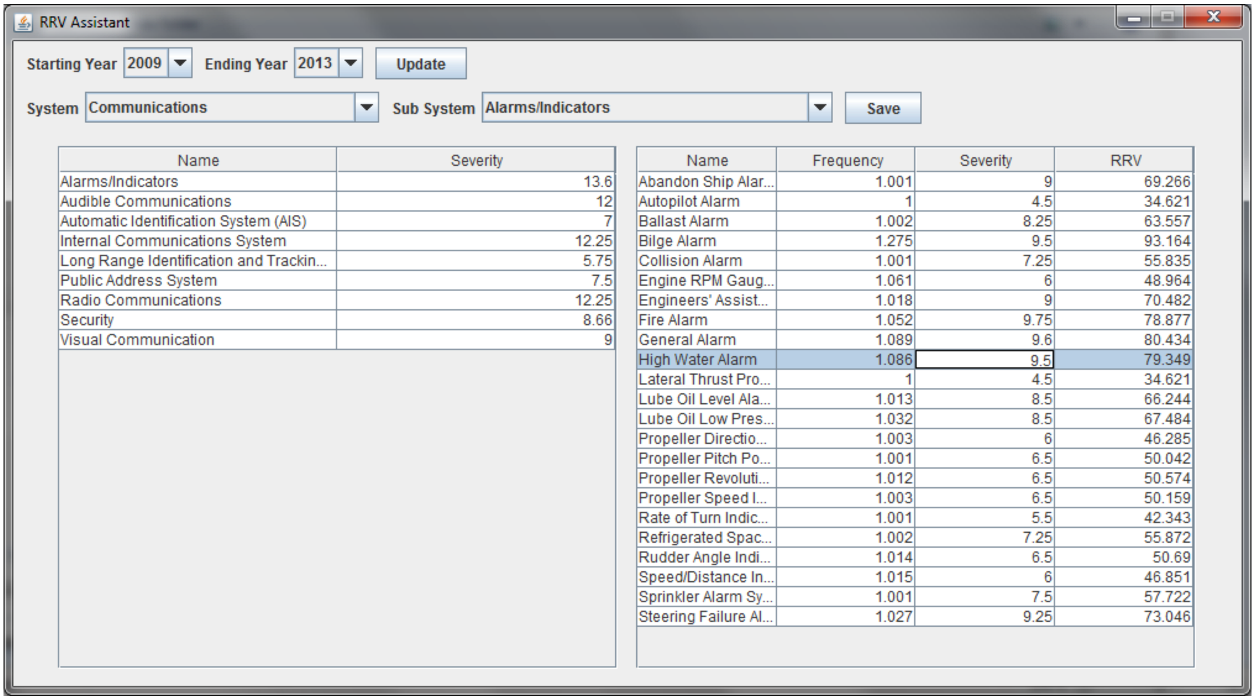
System Communications Sub System Alarms/Indicators

Name	Seve
Alarms/Indicators	
Audible Communications	
Automatic Identification System (AIS)	
Internal Communications System	
Long Range Identification and Trackin...	
Public Address System	
Radio Communications	
Security	3
Visual Communication	9

	quency	Severity	RRV
	1	9	122.4
	1	4.5	61.2
	1	8.25	112.2
	1.033	9.5	133.426
	1.033	7.25	101.825
	1	6	81.6
	1.095	9	134.053
Fire Alarm	1.064	9.75	141.141
General Alarm	1.264	9.6	165.064
High Water Alarm	1.033	9.5	133.426
Lateral Thrust Pro...	1	4.5	61.2
Lube Oil Level Ala...	1	8.5	115.6
Lube Oil Low Pres...	1.033	8.5	119.381
Propeller Directio...	1	6	81.6
Propeller Pitch Po...	1	6.5	88.4
Propeller Revoluti...	1	6.5	88.4
Propeller Speed I...	1	6.5	88.4
Rate of Turn Indic...	1	5.5	74.8
Refrigerated Spac...	1	7.25	98.6
Rudder Angle Indi...	1	6.5	88.4
Speed/Distance In...	1	6	81.6
Sprinkler Alarm Sy...	1	7.5	102
Steering Failure Al...	1.033	9.25	129.915

Figure 19: RRV Sub System dropdown example

From these tables, the user can enter severity values for both components and sub systems. This can be done by double clicking on the “Severity” column for the item that you wish to update the severity for, as seen below in Figure 20. You will notice that as you change the severity, the program automatically updates the RRVs for all of the affected components and/or sub systems. Once you have changed the severity values that you wish, press the “Save” button to save changes.



Starting Year 2009 Ending Year 2013

System Communications Sub System Alarms/Indicators

Name	Severity
Alarms/Indicators	13.6
Audible Communications	12
Automatic Identification System (AIS)	7
Internal Communications System	12.25
Long Range Identification and Trackin...	5.75
Public Address System	7.5
Radio Communications	12.25
Security	8.66
Visual Communication	9

Name	Frequency	Severity	RRV
Abandon Ship Alar...	1.001	9	69.266
Autopilot Alarm	1	4.5	34.621
Ballast Alarm	1.002	8.25	63.557
Bilge Alarm	1.275	9.5	93.164
Collision Alarm	1.001	7.25	55.835
Engine RPM Gaug...	1.061	6	48.964
Engineers' Assist...	1.018	9	70.482
Fire Alarm	1.052	9.75	78.877
General Alarm	1.089	9.6	80.434
High Water Alarm	1.086	9.5	79.349
Lateral Thrust Pro...	1	4.5	34.621
Lube Oil Level Ala...	1.013	8.5	66.244
Lube Oil Low Pres...	1.032	8.5	67.484
Propeller Directio...	1.003	6	46.285
Propeller Pitch Po...	1.001	6.5	50.042
Propeller Revoluti...	1.012	6.5	50.574
Propeller Speed I...	1.003	6.5	50.159
Rate of Turn Indic...	1.001	5.5	42.343
Refrigerated Spac...	1.002	7.25	55.872
Rudder Angle Indi...	1.014	6.5	50.69
Speed/Distance In...	1.015	6	46.851
Sprinkler Alarm Sy...	1.001	7.5	57.722
Steering Failure Al...	1.027	9.25	73.046

Figure 20: RRV Severity Modification example

Please note that after pressing “Update” and “Save” the program might appear to have frozen, but it is working on pulling or updating the data from the database, which is a lengthy process.

Appendix H: RRV Assistant Developer Guide

The RRV Assistance is structured into 3 separate components, the user interface / view, the data objects, and the database interface.

The database interface consists of a MyBatis mapper and a manager. The MyBatis mapper contains all of the queries that are used to fetch data from the database. The manager is an interface between the frontend of the program and the database side, which allows the database implementation to differ without changing the frontend.

Currently, the database implementation and queries are not optimized and take a long time to populate the data with large data sources. This is due to the limited capability of the database that was used as a backend for the program, Microsoft Access. There is no easily available open source JDBC Driver for a Microsoft Access database, and the default ODBC-JDBC bridge does not allow the use of an object-oriented approach with MyBatis.

The data objects are the objects representing the Components, Sub Systems and Systems. These are the objects that contain the data that the user interface displays, as well as contain the logic to make the calculations regarding the RRVs. The manager will create all of these objects using data from the mapper and return them to the user interface.

The database format follows a very similar format to the one used in MISLE. For calculating RRVs, the necessary tables are DEFS, SYSTEMS, SUB_SYSTEMS, and COMPONENTS. The DEFS table mirrors the table which contains vessel deficiencies in MISLE; however the only fields that are used are CALENDAR_YEAR, COMPONENT, SUB_SYSTEM, and SYSTEM. As for the SYSTEMS, SUB_SYSTEMS, and COMPONENTS, these tables store a list of all of the different components and their respective sub system and system. These tables allow for the use of an

Object Oriented approach; however, due to limitations in the ODCB-JDBC bridge, they are not currently being used in this manner. The specification of the tables can be seen below

Table 11: SYSTEMS Table specification

Column Name	Data Type	Column Description
SYS_ID	LONG	The unique ID of the system
SYS_NAME	TEXT	The name of the System

Table 12: SUB_SYSTEMS Table specification

Column Name	Data Type	Column Description
SUB_SYS_ID	LONG	Unique ID of the sub system
SUB_SYS_NAME	TEXT	Name of the sub system
SUB_SYS_SEV	DOUBLE	Severity of the sub system
SYS_ID	LONG	ID of the system which this sub system belongs to
SYS_NAME	TEXT	The name of the system which this sub system belongs to
SUB_SYS_RRV	DOUBLE	The calculated RRV of the sub system

Table 13: COMPONENTS Table specification

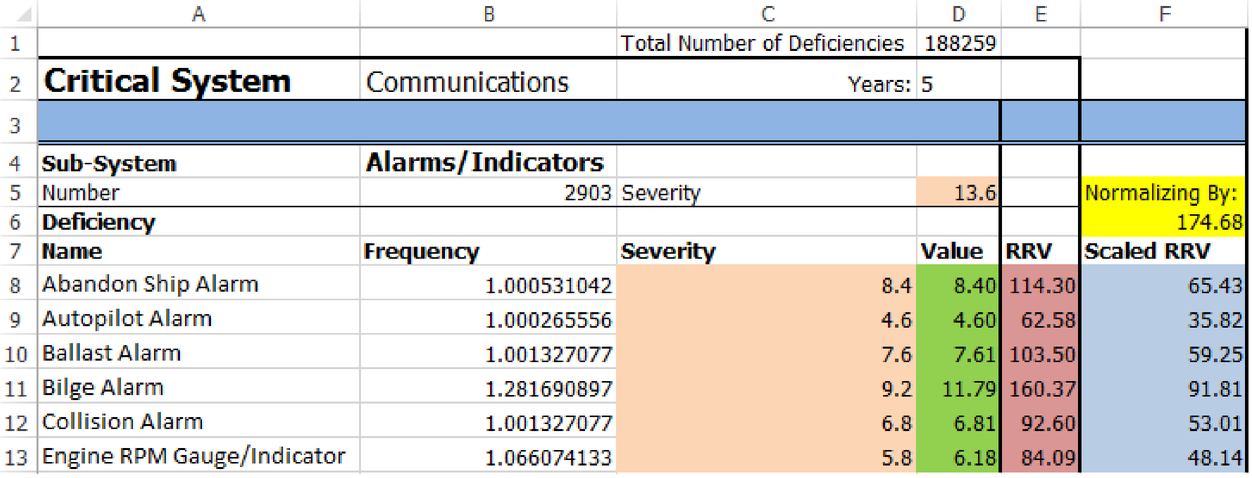
Column Name	Data Type	Column Description
COMP_ID	LONG	Unique ID of the component
COMP_SUB_SYS	TEXT	Name of the sub system this component belongs to
COMP_SYS	TEXT	Name of the System this component belongs to
COMP_NAME	TEXT	Name of the component
COMP_SEV	DOUBLE	The severity of this component
COMP_RRV	DOUBLE	The calculated RRV for this component
COMP_RRV_SCALED	DOUBLE	The scaled RRV for this component
SUB_SYS_ID	LONG	The ID of the sub system this component belongs to

Appendix I: Excel Program User Guide

The manual and image below describe the excel program and the process used to calculate the RRVs.

The RRVs are organized by critical systems, moving from left right in the document, with sub-systems and their respective components listed down the rows.

In the given example, five years' worth of all vessel data is used, as seen in cell D2. The cell D1 above it reflects the total number of deficiencies discovered during inspection over this time period. The sub-system severity value is found in cell B5, and is based on the sum of the three factor ratings of its potential impact on human casualties, property damage and the environment in case of failure.



	A	B	C	D	E	F
1			Total Number of Deficiencies	188259		
2	**Critical System**	Communications	Years:	5		
3						
4	**Sub-System**	**Alarms/Indicators**				
5	Number	2903	Severity	13.6		Normalizing By:
6	**Deficiency**					174.68
7	**Name**	**Frequency**	**Severity**	**Value**	**RRV**	**Scaled RRV**
8	Abandon Ship Alarm	1.000531042	8.4	8.40	114.30	65.43
9	Autopilot Alarm	1.000265556	4.6	4.60	62.58	35.82
10	Ballast Alarm	1.001327077	7.6	7.61	103.50	59.25
11	Bilge Alarm	1.281690897	9.2	11.79	160.37	91.81
12	Collision Alarm	1.001327077	6.8	6.81	92.60	53.01
13	Engine RPM Gauge/Indicator	1.066074133	5.8	6.18	84.09	48.14

Figure 21: Excel Example

The ratings of the sub-system components are seen in cells D8-D13. The frequencies are calculated in cells B8-B13 as:

$$Frequency = sqrt(\frac{\#\ deficiencies\ found\ over\ 5\ years}{total\ \#\ deficiencies\ over\ 5\ years} * 100 + 1)$$

The value of “1” is added to give a default value to deficiencies that have not yet been discovered during inspections to ensure RRV is not calculated to be 0. The square root of the frequency is taken in order to dampen its effect on the final RRV and give higher priority to component’s “Severity” rating.

The “Value” column in D8-D13 is the product of Frequency and Severity. Finally, the RRVs by component are calculated by multiplying “Value” column product by the sub-system Severity value. These RRVs are the final outputs of the program and can be found in cells E8-E13.

Finally, column F contains normalized RRV values, based on the maximum RRV across all existing subsystems. Each RRV in column E is then divided through by this maximum to produce a normalized value within the scale of 1-100.