Title of Thesis: APPLICATION OF INNOVATIVE RISK ANALYSIS TECHNIQUES TO EXAMINE INTERNATIONAL VESSEL SAFETY MANAGEMENT SYSTEM FAILURES

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The International Safety Management (ISM) Code, made mandatory in 1998, dictates the implementation of a Safety Management System (SMS) on every vessel engaged in international shipping. This international standard provides a loose framework around which SMS procedures are required to be written, placing implementation of safety management into the hands of individual companies. In this thesis, vessel safety management systems are viewed through the lens of systems engineering, complete with requirements, user roles, and standards of failure. Furthermore, this thesis analyzes the risks of improperly implemented safety management systems onboard commercial vessels utilizing a hybrid of the Barrier-BowTie Model and Potential Problem Analysis Integration. Additionally, the risk analysis in this thesis stems from trends associated with international (non-United States flagged) vessel detentions in U.S. ports and the related detention-related deficiencies found during U.S. Coast Guard Port State examinations. Lastly, an extensive literature review into similar studies is included.

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by

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List of Abbreviations

ASRS: Aviation Safety Reporting System

FAA: Federal Aviation Administration

IAW: In accordance with

IMO: International Maritime Organization

ISM: International Safety Management (refers to the ISM Code)

PSC: Port State Control

SMS: Safety Management System

SYSML: Systems Modeling Language

U.S.: United States

USCG: United States Coast Guard

Chapter 1: Introduction[1]

Section 1.1: Introduction

In 1998, adherence to the International Safety Management (ISM) Code was made mandatory by the International Maritime Organization (IMO) for all commercial vessels over 500 gross tons that are shipping products internationally. This international standard dictates the implementation of a Safety Management System (SMS), which includes procedures for emergency situations, training, normal vessel operations, reporting emergencies, and the maintenance of critical and non-critical ship systems (About IMO, 2018). Because each vessel is unique and each management company is different, the ISM Code provides only a framework for creating these procedures in coordination with other safety standards and leaves the standard of safety to be set by the individual companies. Member states that are party to the IMO, have developed port state control examination programs to enforce and regulate the ISM code and other IMO standards.

Section 1.2: Problem Statement

The implementation of a Vessel Safety Management System (SMS) is mandated by the International Maritime Organization (IMO) on every vessel engaged in international shipping. However, many vessel SMSs experience failures, especially in their implementation, due to several factors explored in this thesis. This can cause

[1] Portions of this section/chapter have been taken from "Examining Vessel Safety Management through Trends in Vessel Detentions onboard International Vessels from 2004 to 2017" written by Kimberly Gates and Dr. J.W. Herrmann. This paper is currently submitted for publishing by the Journal of Maritime Research.

the vessel to be detained for one or more days, which in turn costs the vessel stakeholders hundreds of thousands of dollars in lost time and expenditures to correct the deficiencies. Furthermore, failures of vessel SMSs can cause maritime accidents, which can lead to severe pollution, death or injury of crew members or bystanders, and/or serious damage or loss of the entire vessel. This thesis uses the Barrier-BowTie Model and the Potential Problem Analysis Method to analyze the risks associated with an improperly implemented SMS.

Section 1.3: System of Interest Description

Subsection 1.3.1: System Description

As described in the system context-level diagram in Figure 1, there are three areas in the vessel safety management system domain: Vessel SMS, Environment, and Users. A Vessel SMS has 9 subsystems, which correspond to the different aspects covered under the International Safety Management Code (ISM Code). The Environment consists of the Vessel Systems and the Vessel's Operating Environment, which include the physical components that are referred to in the SMS. The different users of the Vessel SMS are the Vessel Crew, the Vessel Management Company, the Vessel Owner, the Vessel Chartering Company, the Flag State, and the Port State. The roles of these users are described in Subsection 1.2.2. Please note this section capitalizes the nouns that are used as labels in the systems modeling language (SYSML) diagrams since they are specific descriptors.

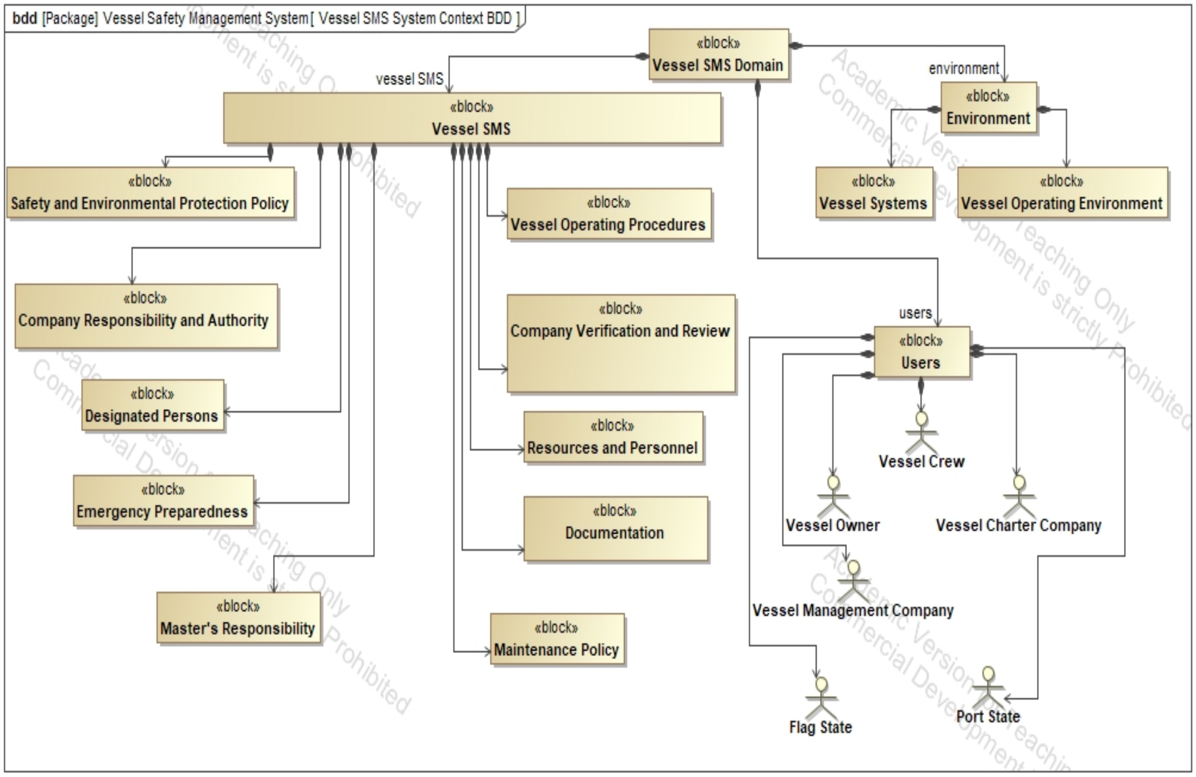


Figure 1. Vessel SMS Context-Level Block Definition Diagram

Figure 2 describes the Vessel SMS subsystems further at the component level.

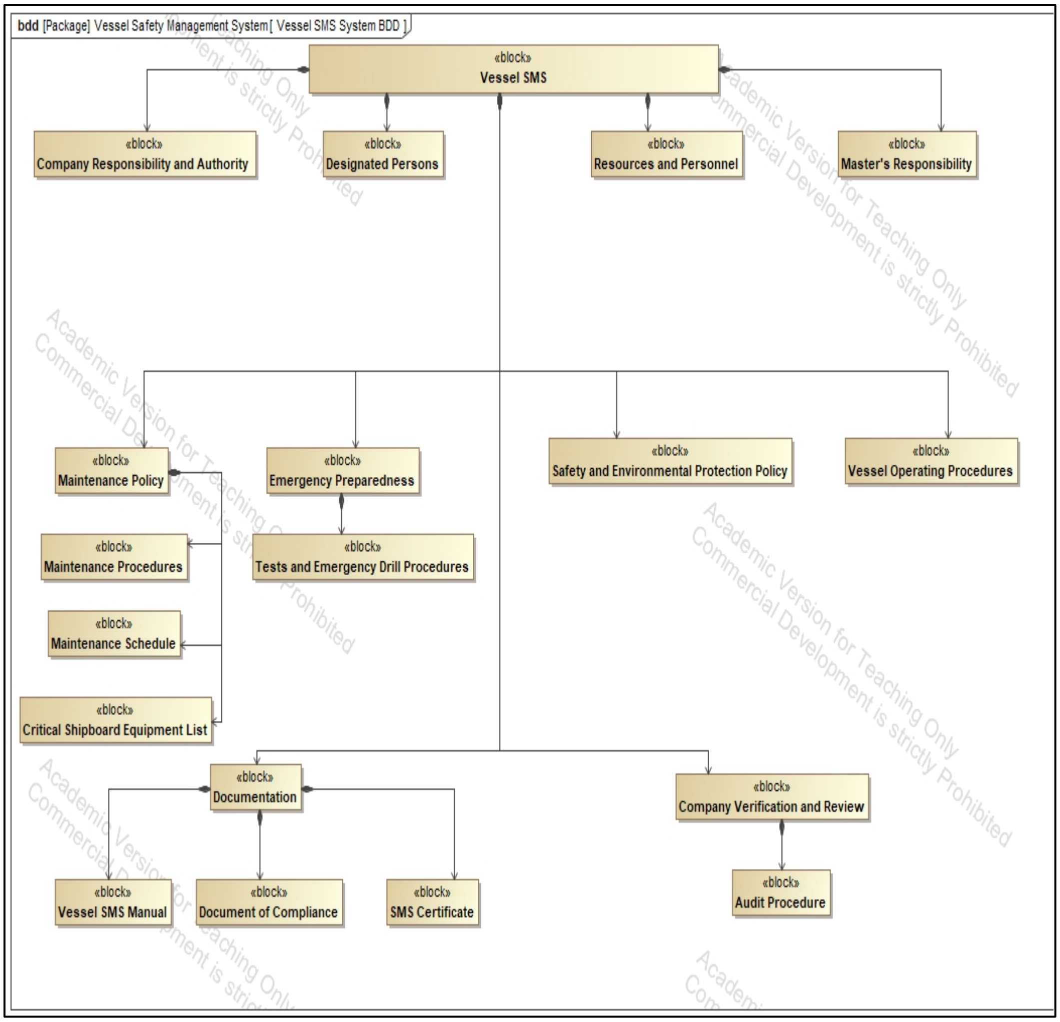


Figure 2.Vessel SMS System-Level Block Definition Diagram

Subsection 1.3.2: Roles of Users

The different users of the Vessel SMS are the Vessel Crew, the Vessel Management Company, the Vessel Owner, the Vessel Chartering Company, the Flag State, and the Port State. The Vessel Crew are the primary users of the Vessel SMS, and include the vessel's Master, the members of Deck Department including the Chief Officer, and the members of the Engineering Department including the Chief Engineer Officer. They are responsible for implementing the SMS onboard the vessel and carrying out the associated responsibilities outlined in the SMS depending on their role in the crew. The Vessel's Master is specifically responsible for the safety of the vessel and its crew.

The Vessel Owner owns the vessel that is being used by the Vessel Chartering Company to ship goods and products from one port to another. The Vessel Owner is responsible for writing the SMS, specifically the SMS Manual in conjunction with the Vessel Management Company. The Vessel Owner and the Vessel Management Company often have intertwined roles with the owner being the managing owner and head of the Vessel Management Company.

The Vessel Management Company is responsible for administrative aspects of the international shipping business for the vessel to include hiring, handling of contracts, pay, leave, and schedules for the Vessel Crew. The Vessel Management Company is also responsible for conducting regular audits and inspections of all the different subsystems of the Vessel SMS to ensure compliance with the ISM Code. Lastly the Vessel Management Company liaises with the Vessel Chartering Company on schedule, shipping requirements, and safety of cargo.

The Vessel Chartering Company owns the cargo (products or goods) that are being shipped internationally. They have a joint responsibility with the Vessel Management Company to ensure the cargo is packaged and shipped in accordance with the Vessel SMS and the ISM Code.

The Flag State is the country under which the vessel sails. The Flag State has additional regulations in addition to the IMO regulations that the vessel must follow. Furthermore, the Flag State is responsible for auditing the vessel's SMS and ensuring compliance with ISM Code. The Flag State also issues the Document of Compliance

Certificate and the SMS Certificate. Often, the Flag State will appoint classification society representatives to conduct these annual audits of the SMS and issue certifications, however, the ultimate authority lies with the Flag State.

Finally, the Port State is the country where the vessel makes port. Port States employ Port State Control Officers who conduct annual examinations when a vessel enters a port. These examinations include a safety component and a security component. The safety examinations include a review of the SMS manual and certificates and ensuring the vessel and its crew are complying with the ISM Code as written in the SMS Manual.

Subsection 1.3.3: Vessel Safety Management Systems Development Process

The requirements for developing a Vessel SMS are specified in the ISM Code. The principal requirement is that each system and subsystem detailed in Section 1.3.1 must be included in the Vessel SMS. The main document that contains the Vessel SMS is called the Vessel SMS Manual. Each vessel must have an individually tailored SMS manual. The vessel management company is responsible for developing the SMS and creating the vessel specific SMS manual. Once the vessel SMS is created, it is implemented and evaluated by the vessel's crew. Then, it undergoes an initial audit by the vessel's Flag State, usually through an authorized Classification Society. This audit process verifies that the vessel SMS, including the SMS manual, meets the requirements of the ISM Code as written and is implemented properly onboard the vessel. If requirements are not met or there are deficiencies with the implementation of the SMS, the Flag State (or Classification Society) will issue a document of non-conformity, which needs to be corrected within a specified timeframe. A non-conformity is similar in nature to a deficiency, explained in Subsection 1.3.4, however, it is not typically associated with a financial penalty and is often quickly resolved. These non-conformities can include restrictions to specific operations until they are resolved, but often do not stop the vessel from operating or carrying cargo completely. Only the Flag State (or Classification Society) can resolve non-conformities on the vessel.

Additionally, during the initial audit process, the SMS Certificate and Document of Compliance are issued, certifying the SMS onboard meets the requirements of the ISM Code. These certificates are typically issued even if there are non-conformities on the vessel; the document of non-conformity acts as an addendum to the certificates.

Subsection 1.3.4: Defining Failure of Vessel Safety Management Systems

For the purposes of this thesis, failure of a vessel SMS is defined by the lack of full implementation of the approved SMS, which is constitutes a violation of the International Safety Management (ISM) Code. It is assumed in this thesis that the SMS onboard any vessel has undergone the appropriate approval process, which includes approval by the Flag State and the vessel's management company. This approval process validates that the vessel SMS, created by the vessel management company, complies with the ISM Code and is specific to the vessel type, engineering systems onboard, and the crew makeup.

Violations of the ISM Code are also referred to as a type of deficiency for the purposes of this thesis. There are three ways ISM deficiencies can be identified for correction. First, the vessel's crew, often in conjunction with the vessel's management company, conducts regular reviews of the SMS, which usually includes a review of one subsystem at a time. Secondly, the vessel's Flag State conducts annual audits of the vessel SMS which includes looking at the implementation of every subsystem of the SMS to verify compliance with ISM Code. Lastly, several Port States will conduct safety examinations of the vessel, which include a review of how the vessel is implementing the approved SMS onboard. Port state examinations are less focused on whether the SMS meets the ISM Code and more on the implementation of already approved SMS. Port state examinations are conducted annually in the United States on vessels that frequent the United States and do not have a history of safety or security deficiencies. This thesis will focus on the failures of a vessel SMS found during Port State Control examinations in the United States from 2004-2017.

Section 1.4: Research Questions

This thesis will endeavor to answer the following research questions. First, what are the risks (causes) of vessel detentions associated with failures to implement a vessel SMS? This will be answered through a detailed data and risk analysis, specifically focusing on the failure to implement vessel SMS on international commercial vessels identified by the U.S Coast Guard during port state control examinations.

Secondly, how can the Barrier-BowTie and the Potential Problem Analysis Method be integrated and utilized to analyze those risks? These methods have been individually applied to SMSs of different fields including aviation. However, Barrier-

BowTie and Potential Problem Analysis have yet to be integrated in the area of maritime SMS.

Lastly, which mitigation strategies would be most effective to prevent the risks identified in the analysis? The goal of the risk analysis is to highlight hazards that pose the most severe risk to the stakeholders. This thesis will explore and propose specific mitigation strategies based on the risk analysis results.

Chapter 2: Literature Review

Section 2.1: Literature Review[2]

Since the ISM Code was made mandatory for international commercial vessels in 1998, the risks associated with failing to properly implement an effective SMS has been a key research topic. Størkersen et al. (2017) analyzed the Norwegian high-speed craft industry and the influence that regulators, the ISM code, and organizational factors have over operational safety. After conducting 47 interviews with maritime authorities, company management, and shipboard crews, Størkersen et al. drew the following conclusions:

1. In general, it is perceived that safety regulations (ISM Code) increase safety awareness onboard vessels.
2. Although companies are responsible for determining what is safe enough due to self-regulation in ISM Code, they are still looking to the government to provide the definition.
3. There is an over-reliance on the checklist and not on critical thinking when it comes to safety critical decisions.
4. In general, safety-related administrative work is deemed unimportant, and takes time away from safety critical tasks.

The last conclusion highlights a potential threat to failing to implement a vessel SMS, which falls under the categories of crew complacency and increased complexity.

[2] Portions of this section have been taken from "Examining Vessel Safety Management through Trends in Vessel Detentions onboard International Vessels from 2004 to 2017" written by Kimberly Gates and Dr. J.W. Herrmann. This paper is currently submitted for publishing by the Journal of Maritime Research.

Simplifying procedures and minimizing distractions on the bridge were proposed as two solutions to these issues (Storkensen et al., 2017).

Lappalainen (2008) also discussed the challenges with implementing SMSs onboard Finnish vessels and proposed a performance measurement system that would include safety criteria such as accident rate/injury frequency, vessel delays, insurance claims, and safety culture. The main problems with this assessment of safety was that there is a lack of standard interpretation for ISM Code and that mariners were reluctant to report safety issues for fear of reprisal (Lappalainen 2008). Within the vessel SMS, there are currently no requirements for confidential reporting in the ISM Code, and the fear of reprisal for crew members is a significant barrier to the implementation of an effective vessel SMS.

Furthermore, there are many challenges to quantifying and establishing safety-related analysis techniques. Sii et al. (2001) identified several problems to quantifying safety assessments, including a lack of safety data, the costs of reducing risk, and limited operational experience with newer systems. They proposed three safety optimization frameworks for assessing risk to include a design trade-off analysis, a decision support system based on artificial neural networks (ANN), and a fuzzy logic-based system.

Hänninen and Kujala (2014) used Finnish port state control inspection and accident data (from 2004 to 2010) and Bayesian belief networks (BBNs) to explore how port state control (PSC) inspection results (deficiencies) are linked to each other and maritime accidents. The data used in this study was from the Finnish port state control inspection database (2009-2011), Helsinki accident database (2004-2010), and

VTS incident and violation data (2004-2008). They concluded that ship type was the most important knowledge factor for decreasing the uncertainty in accident involvement, especially when linked with structural condition and radio communication information. Analogous to this thesis, this study analyzed port state control inspection data and successfully proved there is a relationship between deficiencies and vessel accidents.

Similarly, Trucco et al. (2008) used BBNs and fault tree diagrams to model organizational and operation factors and analyze the risk of specific types of accidents. They utilized expert opinion as prior knowledge and updated this with Italian maritime accident data to develop conditional probabilities and links between accident data and organizational factors to better analyze risk. This study adds to the knowledge about the effectiveness of vessel safety programs by analyzing data over a fourteen-year period and presenting trends that provide new insights.

Section 2.2: Barrier BowTie Model Literature Review

As seen in an article by Trbojevic and Carr (2000) and in an article by Clothier et al. (2018), the Barrier BowTie Model is a risk analysis model that utilizes graphics to represent the different components of the risk analysis, including the risk management/controls component. This model has been used by many different industries including the oil and gas industries, medical field, and aviation sector. Trbojevic and Carr used Barrier BowTie models to analyze the risks and hazards for improving port safety in the hopes of reducing navigation errors and vessel accidents. They also integrated hazard analysis into the Barrier BowTie Model and utilized the Barrier BowTie model in place of a traditional fault tree diagram. The advantages to the Barrier BowTie model that they identified were that it is a great communication tool for stakeholders and that it is a useful day-to-day risk management tool for port personnel since it connects everyday tasks to hazard control and recovery measures (Trbojevic and Carr, 2000).

Clothier et al. (2018) applied Barrier BowTie models to the hazards and risks posed by remotely piloted aircraft to persons on the ground. They identified several advantages of utilizing Barrier BowTie models in their analysis. First, Barrier BowTie models allow for the incorporation of many different risk analysis components including the threats, causes, consequences, and controls (barriers). Furthermore, the relationships that exist between these components are easily distinguished in a Barrier BowTie model. Additionally, multiple domains of risk can be incorporated in Barrier BowTie models, such as human error, organizational risk, mechanical system failure, and procedural error. Barrier BowTie models can also be used as a framework and combined with other risk analysis models and techniques, such as failure mode, effects, and criticality analysis (FMEA) and human factor analysis. Lastly, Barrier BowTie models emphasize the importance of controlling risks and establishing the layers of controls that are associated with threats and consequences (Clothier et al. 2018).

On the other hand, they also acknowledged some disadvantages to using Barrier BowTie models. Each Barrier BowTie model has only one top event and additional models could have dependencies that are not easily distinguished in the model due to these separate top events. Furthermore, the barriers in the model misleads the viewer to think that all the barriers are independent, however, barrier dependence can exist. These dependencies cannot be easily displayed in the model and therefore need to be identified in a separate analysis (Clothier et al. 2018).

Section 2.3: Further Research Questions

This literature review draws out many different techniques for analyzing vessel SMSs and identifying safety risks onboard vessels. An additional research question that this thesis will seek to answer is if a relationship can be drawn between port state control deficiency data and the causes of vessel SMS failures.

Chapter 3: Approach[3]

Section 3.1: Data Collection Approach

The goal of a port state control program is to identify and eliminate substandard vessels from the territorial waters of that nation. A substandard vessel is defined in Procedures for Port State Control as "a ship whose hull, machinery, equipment, or operational safety is substantially below the standards required by the relevant convention" (Procedures for Port State Control, 2017). If a vessel is found to be substandard during a port state control examination, then the vessel is detained in the waters of that port state until the severe deficiency can be rectified. This action is called a vessel detention and is only taken when the port state deems that the vessel or its crew are a danger to themselves, the environment or other vessels (Procedures for Port State Control, 2017).

In the United States, the U.S. Coast Guard administers the port state control program and conducts two types of vessel examinations in accordance with (IAW) the Procedures for Port State Control: safety examination and security examination. A safety examination verifies the safe operation of the various essential systems onboard the vessel. A security examination ensures adequate control of cargo and persons on and off the vessel. Every international vessel that arrives at a U.S. port is screened to determine if the vessel needs to undergo a port state control examination. In general, an international vessel will undergo an annual port state control examination, which will include both safety and security examinations.

[3] Portions of this chapter have been taken from "Examining Vessel Safety Management through Trends in Vessel Detentions onboard International Vessels from 2004 to 2017" written by Kimberly Gates and Dr. J.W. Herrmann. This paper is currently submitted for publishing by the Journal of Maritime Research.

Vessels with a history of serious safety or security deficiencies may be examined more frequently.

This thesis used two datasets built from U.S. Coast Guard data systems. The Coast Guard Business Intelligence (CGBI) system compiles deficiency and detention data from a vessel inspection database. The first dataset was created by searching the CGBI for a list of detention-related deficiencies from 2004 to 2017 with the following search criteria: Vessel Flag: Foreign, Detention: Yes, and Activity Status: Closed. Table 1 summarizes the fields of data that were collected on June 18, 2018.

Table 1. Fields of Data Collected from USCG Data System

Field	Units	Type of Data
Activity Date	Month/Day/Year	Date
Fiscal Year	Year	Date
Fiscal Quarter	N/a	Numerical
Calendar Year	Year	Numerical
Calendar Quarter	N/a	Numerical
Month	N/a	Numerical
Activity Status	N/a	Text
Activity Close Date	Month/Day/Year	Date
Data Import Source	N/a	Text
Area	N/a	Text
District	N/a	Text
Department	N/a	Text
Deficiency Status	N/a	Text
Issue Date	Month/Day/Year	Date
System	N/a	Categorical
Subsystem	N/a	Categorical
Component	N/a	Categorical
MISLE Vessel	N/a	Numerical

ID		
Vessel Name	N/a	Text
Vessel Class	N/a	Categorical
Vessel Type	N/a	Categorical
Vessel Service	N/a	Categorical
Classification Society	N/a	Categorical
Inspection Subchapter	N/a	Categorical
Flag State (Abbreviated)	N/a	Categorical
Vessel Age	Years	Numerical
Length	Feet	Numerical
Default Gross Tonnage	Gross Tons	Numerical
Regulatory Gross Tonnage	Gross Tons	Numerical
ITC Gross Tonnage	Gross Tons	Numerical

This search resulted in the collection of 15,677 detention-related deficiencies (referred to as simply "deficiencies" in following sections). These deficiencies were further sorted by Year, Vessel Age, Vessel Type, and System using Microsoft Excel. The still open detention activities were not included in the dataset since they included on-going investigations/cases.

A second dataset was created in Microsoft Excel through the collection vessel information from the U.S. Coast Guard's annual Port State Control reports (U.S. Coast Guard, 2018). The information was compiled from 2004 through the 2017 editions of this report. It included general arrival data, number of security and safety examinations, and number of unique ship arrival data.

Section 3.2: Data Analysis Approach

Microsoft Excel was used to graph and analyze the general data trends in both datasets. These included the trends in vessel arrivals, port state control examinations, deficiencies, detentions, and age of vessels detained from 2004-2017. In addition to Microsoft Excel, TreeMap software was used to analyze data trends of the categorical data, using the Excel spreadsheet with the CGBI deficiency data as an input ("TreeMap", 2018). The data trends that were analyzed in this thesis were trends based on deficiency system, trends based on vessel age, and trends based on vessel service.

Furthermore, Matlab was utilized to examine the trends in vessel age through a k-means cluster analysis ("k-means Clustering", 2019). The number of clusters (k) was varied from 2 to 10 in order to see how the cluster patterns changed. This analysis was performed in order to better understand the age clusters based on the numbers of SMS detentions and the deficient SMS components. The input for this k-means analysis included only vessel detentions that contained SMS deficiencies and only the first instance of such a detention for a particular unique vessel. This was done to remove any duplications of the same vessels across multiple age categories. Lastly, the data was normalized by taking the number of deficiencies in each SMS component category and dividing them by the number of SMS detentions for each age.

Section 3.3: Risk Analysis Approach

Subsection 3.3.1: Barrier BowTie Model

The Barrier BowTie Model is a risk assessment tool that creates a structured analysis of risky scenarios in order to communicate how they develop, and the consequences and barriers associated. As described in BowTie XP's "Bowtie Methodology Manual," this risk assessment method includes an eight-step process to analyze the risk scenario and develop the model. These steps include:

1. Identify Hazards
    a. Hazards are defined as controlled elements of a scenario that introduce risk. These can be specific activities, situations, or physical hazards. For example, driving a car is a hazard because it is a controlled situation, but introduces risks into the scenario of everyday routine.
2. Identify Top Events
    a. Top Events are based on the hazards identified in Step 1 and are defined as the events that causes control over a hazard to be lost. Due to this event, there is a potential exposure to the stakeholder or user(s) of the system.
3. Identify Threats
    a. Threats are defined in this model as the independent causes of the top events.
4. Identify Consequences
    a. The consequences are the undesired, harmful effects of the top event to the user or stakeholder.

5. Identify Preventive Barriers
    a. Preventive barriers are controls placed in the system that prevent the top event from occurring.
6. Identify Recovery Barriers
    a. Recovery barriers are controls placed in the system that mitigate the consequences that result from the top event.
7. Identify Escalation Factors
    a. Escalation factors are defined as conditions or actions that would allow the barrier (preventive or recovery) to fail.
8. Identify Escalation Factor Barriers
    a. Escalation Factor Barriers allow the preventive or recovery barrier to remain in place despite the potential for an escalation factor.

In this thesis, all eight steps will be utilized to create a model of the risks involved with implementing a vessel SMS and work through mitigation strategies (barriers). BowTieXP's software will be used to build the risk analysis model.

Subsection 3.3.2: Barrier BowTie Selection

The Barrier BowTie Model was selected for this thesis because of its ability to display a majority of the risk analysis components in a cohesive model, as well as its emphasis on control measures to be taken to prevent vessel detentions caused by SMS failures. Utilizing a model will allow for easier risk communication to stakeholders because it is easy to understand and interpret. Furthermore, a Barrier BowTie model is appropriate for analyzing risks associated with SMS implementation failures because it allows for the incorporation of the results of data analysis (see Section 3.1).

Additionally, it can be used in conjunction with Potential Problem Analysis, which is a well-known risk analysis method to analyze safety related risks. Lastly, Barrier BowTie models have been proven effective in the aviation sector to analyze specific safety management risks, such as in Clothier, Williams, and Hayhurst (2018), described in Section 2.2.

Subsection 3.3.3: Potential Problem Analysis

Potential Problem Analysis (PPA) is a risk analysis method that was created by Charles Kepner and Benjamin Tregoe and outlined in their book, The New Rational Manager (1997). This method is based on the premise that good managers are constantly looking toward future problems and trying to mitigate their consequences. This book describes Potential Problem Analysis as a framework with the following steps for analyzing and mitigating risk:

1. Define the Action: The end state or goal of the action to be taken.
2. List all Potential Problems associated: The potential unfavorable results that need to be addressed in this analysis.
3. Identify the causes of the potential problems.
4. Ascertain actions to prevent the causes of potential problems.
5. Define measures to mitigate effects should the problem occur.
6. Place subsystems within the system to indicate that a potential problem has occurred.

Subsection 3.3.4: Integrated Risk Analysis

In this thesis, Potential Problem Analysis will be integrated into the Barrier BowTie Model to create a complete risk analysis to include mitigation strategies. All steps of the Barrier BowTie Model will be utilized and a graphical model created using information generated through Potential Problem Analysis. Following the steps of PPA outlined in Section 3.3.3, I will integrate the Barrier BowTie steps using the following process. First, in the "Define" step of PPA, the action will be defined as creating a Barrier BowTie Model that analyzes vessel SMS failures. In the second step of PPA, the potential problem is characterized as the top event in the Barrier BowTie model and in this thesis, the top event will be vessel detention due to vessel SMS failures. Thirdly, the causes of the top event/potential problem will be identified and these causes will be the threats in the Barrier BowTie Model. Next, during the fourth step of PPA, the actions to prevent the causes or threats are the preventive barriers, and will be identified in this step. Also, in this step, the escalation factors and barriers will be identified since it is related to the preventive barriers. The fifth step of PPA includes describing measures to mitigate effects if the problem occurs. During this step, the recovery barriers of the Barrier BowTie Model will be defined. This step will complete the Barrier BowTie Model. Lastly, in step six of the PPA, the current system triggers, which identify that the top event/potential problem has occurred, will be listed in a separate table. The Barrier BowTie Model and the system trigger table are the two outputs of the risk analysis.

Chapter 4: Data Analysis[4]

Section 4.1: General Vessel Data

Subsection 4.1.1: Vessel Arrival Data

From 2004 to 2017, there was an average of 77,438 vessel arrivals/year into the ports of the United States. This included each arrival into a port and repeated vessel arrivals along regular routes throughout the year. As shown in Figure 3, vessel arrivals have varied narrowly per year from 2004 to 2017 with a sharp increase in 2006.

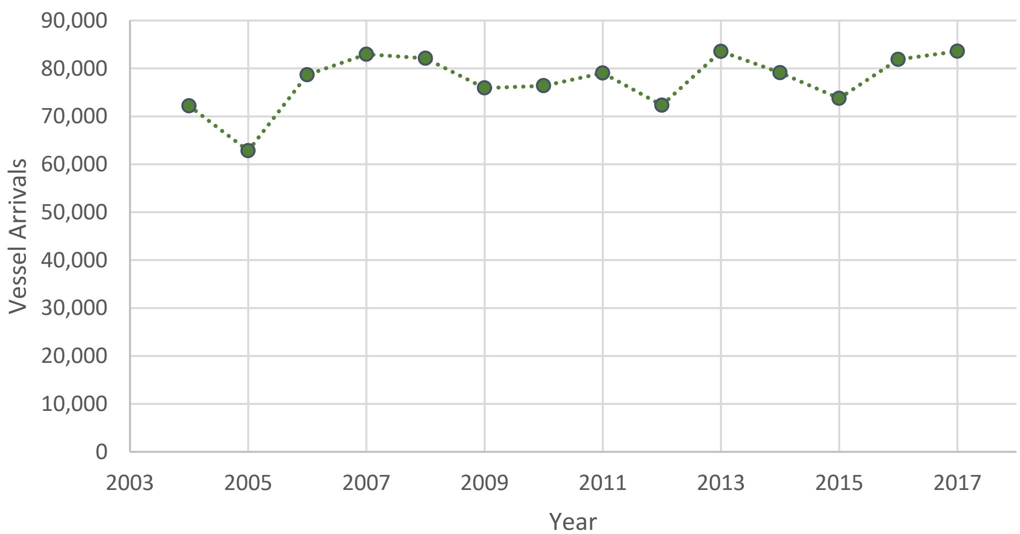


Figure 3. Total Vessel Arrivals in U.S. Ports from 2004-2017

In looking at the number of unique vessels arriving in U.S. ports, however, there has been a steady increase from 2004 to 2017. This is shown in Figure 4. The

[4] Portions of this chapter have been taken from "Examining Vessel Safety Management through Trends in Vessel Detentions onboard International Vessels from 2004 to 2017" written by Kimberly Gates and Dr. J.W. Herrmann. This paper is currently submitted for publishing by the Journal of Maritime Research.

average number of unique vessels arriving to the U.S. is 8,846 vessels in that same time period.

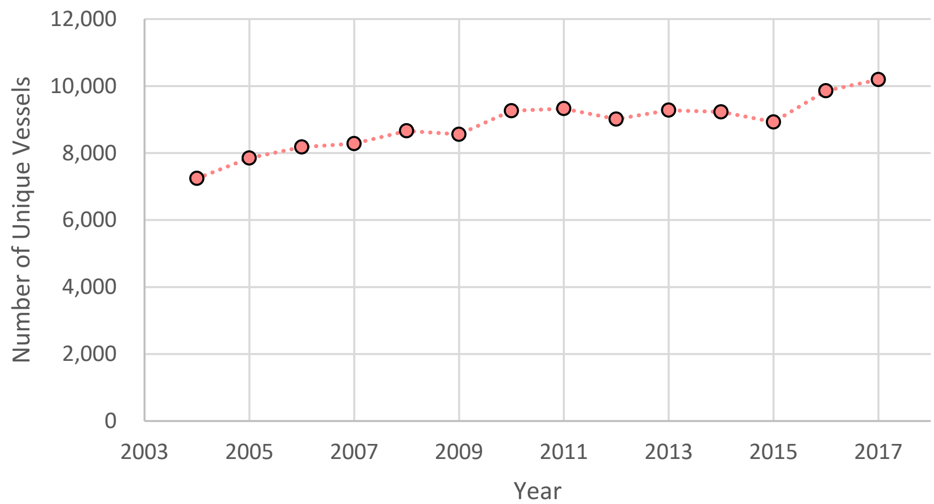


Figure 4. Unique Vessel Arrivals from 2004-2017 to U.S. Ports

Subsection 4.1.2: Vessel Examination, Detention, and Deficiency Data

From 2004 to 2017, the U.S. Coast Guard conducted a total of 139,169 port state control safety examinations. In stark contrast to the increase in unique vessel arrivals, the number of port state control examinations steadily decreased from 2004 to 2017, with the exception of 2008 which showed a 10% increase from the previous year. Figure 5 shows this decreasing trend in port state control safety examination in the United States.

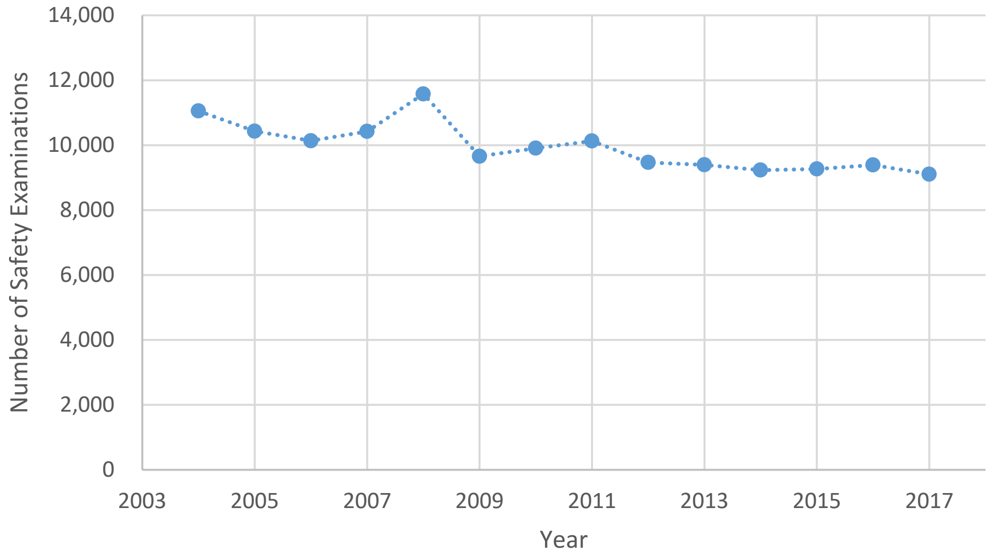


Figure 5. Port State Control Safety Examinations from 2004-2017 in U.S.

From 2004 to 2017, the total number of detentions was 2,072. As seen in Figure 6, the number of detentions remained steady with an average of 142 per a year since 2004. The greatest number of detentions was 216 in 2015. Since that sharp increase in 2015, the detentions in 2016 and 2017 were remarkably low.

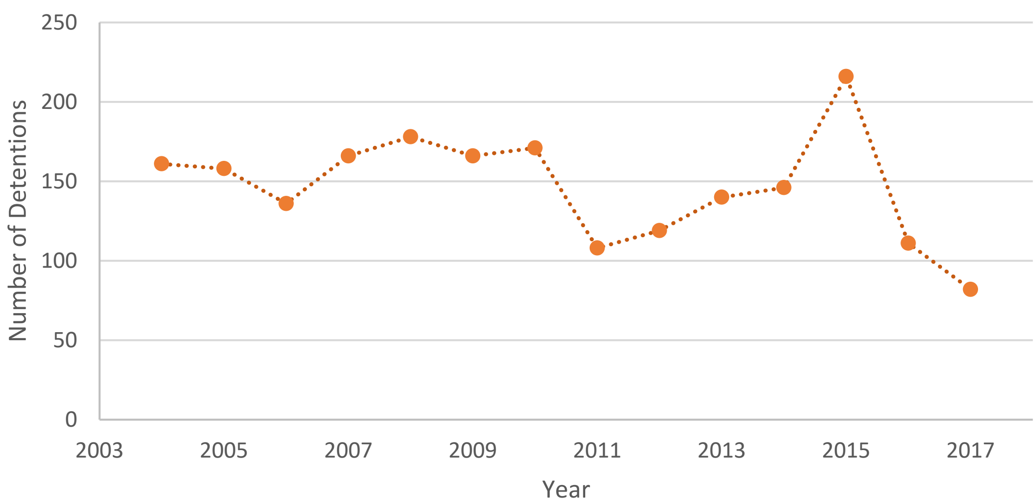


Figure 6. Vessel Detentions from 2004-2017 in United States

In that same time period, the total number of detention-related deficiencies on foreign flagged vessels was 15,677 with an average of 8 deficiencies for each detention. As seen in Figure 7, the number of deficiencies per a year follows a similar pattern as the number of detentions.

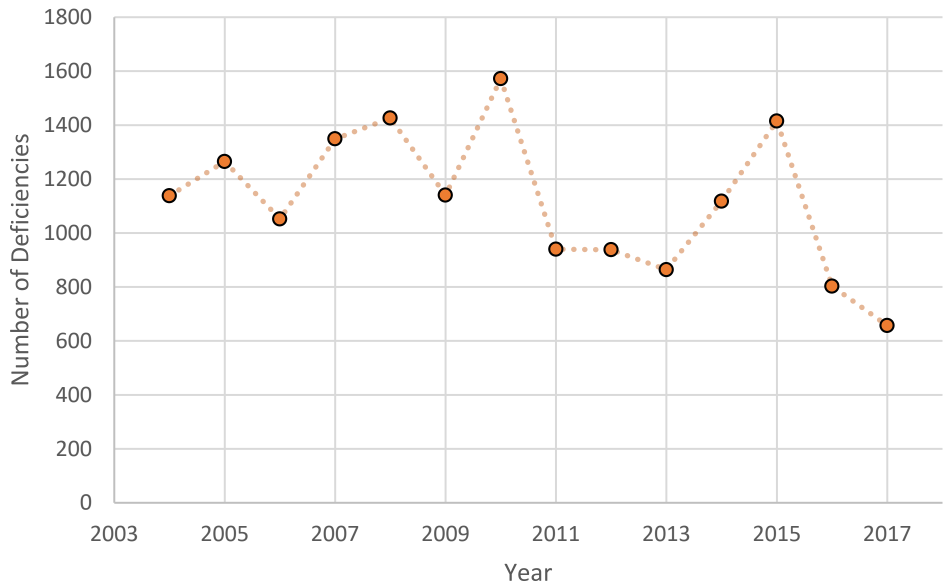


Figure 7. Detention-Related Deficiencies from 2004-2017

<u>*Section 4.2: Data Trends by Deficiency System*</u>

When each deficiency is entered into the U.S. Coast Guard's PSC examination database, it is classified by the system and subsystem which is deficient. For example, if the sprinkler system in the engine room does not operate, this deficiency would be inputted as a firefighting deficiency under the subsystem of fire suppression. Deficiency data is recorded by the PSC Examiner and tabulated in the CGBI database. To represent the number of deficiencies by system, TreeMaps were created that show the results as blocks. Each small block has the same area and represents one deficiency. The color of the block indicates the system, subsystem, or component type. The list of systems and correlated subsystems is in Appendix A.

In Figure 8, the detention-related deficiencies from 2004 to 2017 are organized by system. The number of deficiencies for each system are represented by the number of blocks under each system category. It can be seen that Operations/Management (18%), Firefighting (13.8%), Engineering (13.6%), and Documentation (11.7%) are the four system categories with the most deficiencies during detentions from 2004-2017.

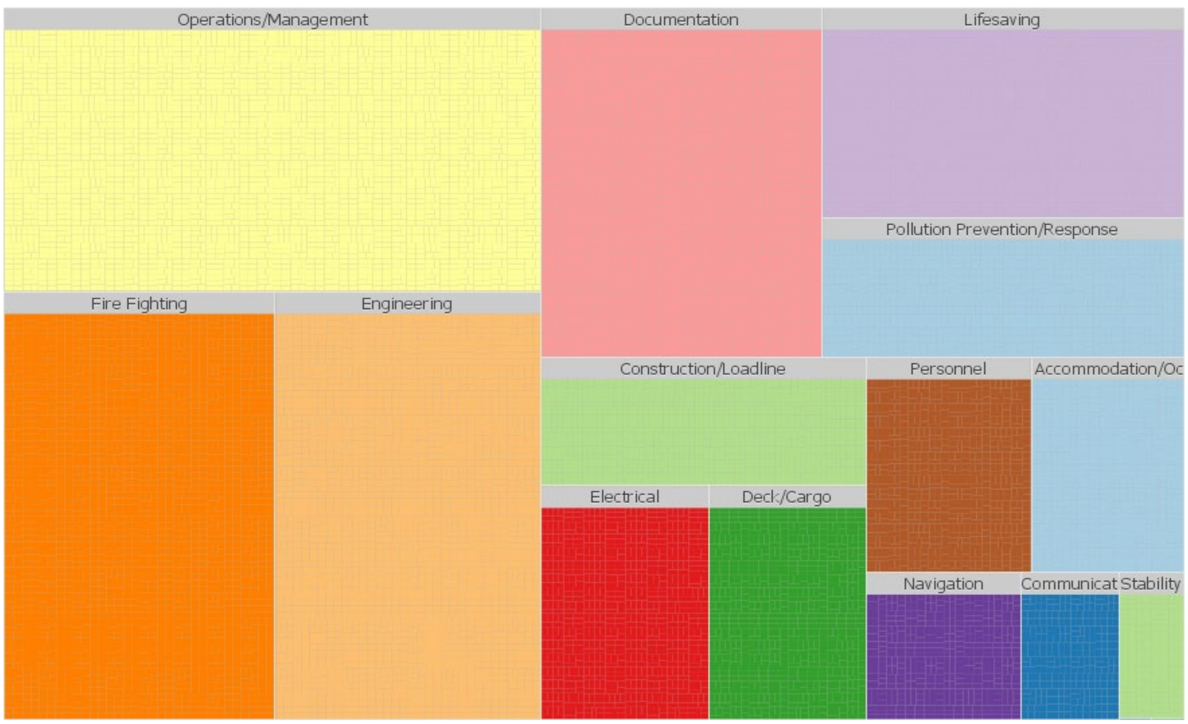


Figure 8. TreeMap of Detention-Related Deficient System-Types Organized by Most Frequent (2004-2017)

As seen in Figure 9, among the deficiencies in the Operations/Management system, the subsystems Vessel Safety Management (34%) and Security (33%) have the most detention-related deficiencies.

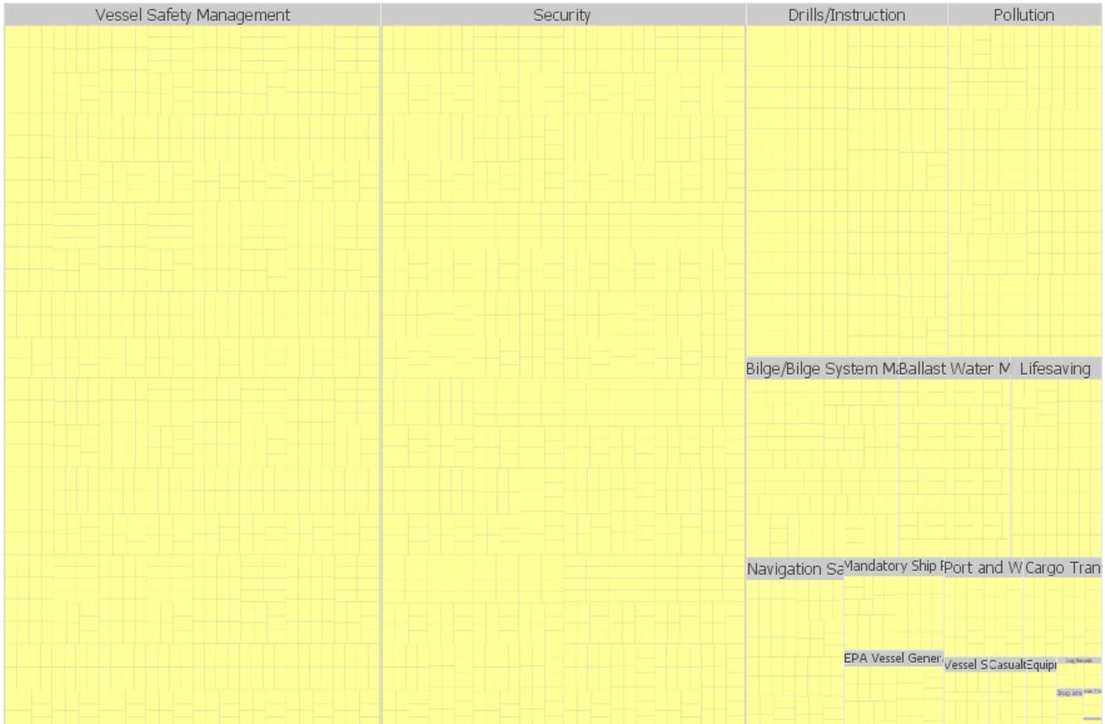


Figure 9. TreeMap of Operations/Management Subsystems from 2004-2007

Figure 10 summarizes the SMS components under SMS Subsystem in a pareto chart. This pareto chart emphasizes that under the Vessel Safety Management subsystem, the most commonly deficient component is the Maintenance of Ship/Equipment, making up approximately 40% of all SMS deficiencies. This demonstrates that a failure to maintain the vessel and ship equipment is the most common issue onboard vessels in relation to implementing a vessel SMS, which will deem the vessel unsafe to operate and result in a detention. The pareto chart in Figure 20 also shows that the following SMS deficiency components account for 70% of all the SMS deficiencies resulting in detentions: Maintenance of Ship/Equipment, Company Responsibility/Authority, Master Responsibility/Authority, and Documentation Maintenance/Control. These categories will be the focus of the risk analysis in Chapter 5. Table 2 underscores the number of deficiencies in each SMS component category.

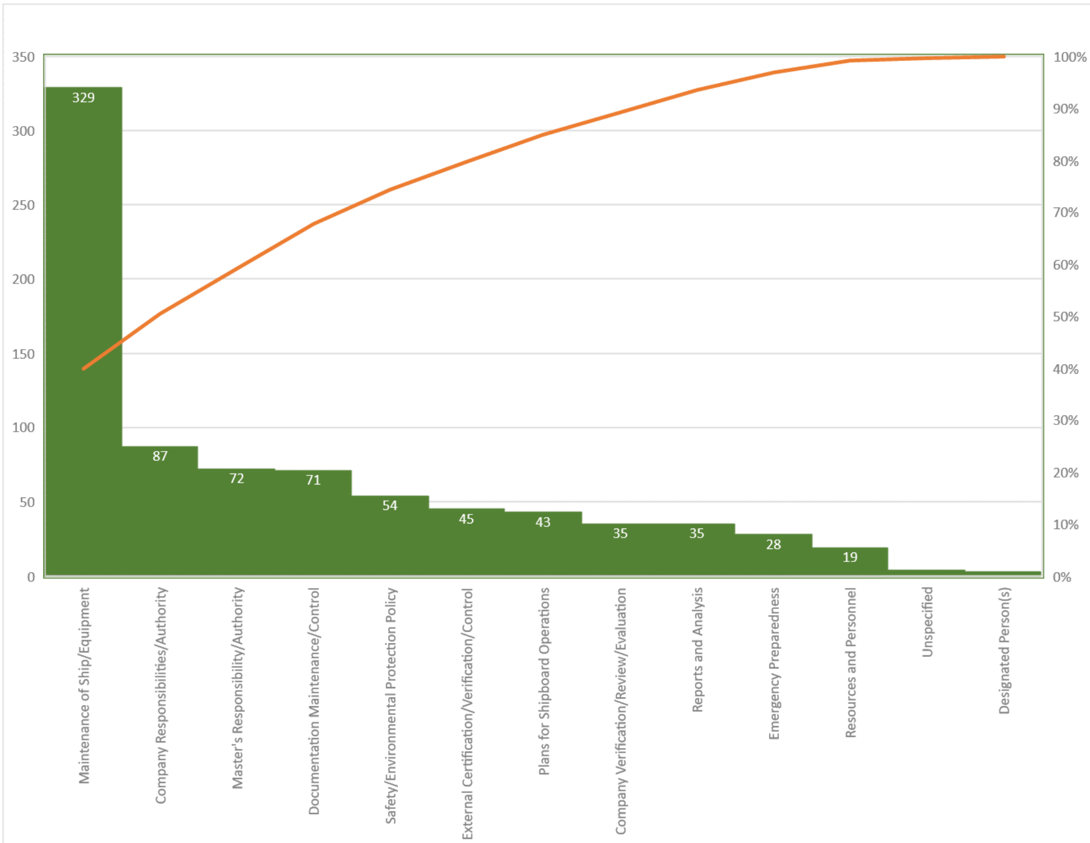


Figure 10. Pareto Chart of SMS Component Deficiency Categories and Associated Counts

Table 2. Number of Safety Management System Deficiencies (Resulting in Detentions) by Component from 2004-2017

SMS Components	Number of Deficiencies
Company Responsibilities/Authority	87
Company Verification/Review/Evaluation	35
Designated Person(s)	3
Documentation Maintenance/Control	71
Emergency Preparedness	28
External Certification/Verification/Control	45
Maintenance of Ship/Equipment	329
Master's Responsibility/Authority	72
Plans for Shipboard Operations	43
Reports and Analysis	35
Resources and Personnel	19
Safety/Environmental Protection Policy	54
Unspecified	4

Section 4.3: Data Trends by Vessel Age

The average ship age of all vessels detained from 2004 to 2017 was 29 years. As shown in Figure 11, the average ship age of detained vessels per a year steadily decreased in a near linear fashion from 36 in 2004 to 22 in 2017.

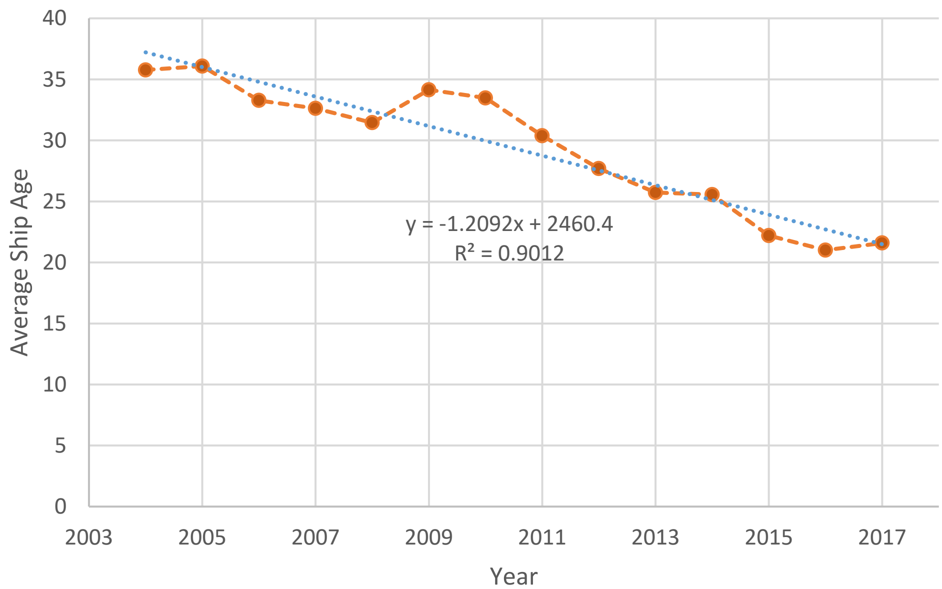


Figure 11. Average Ship Age for Vessels Detained from 2004-2017

As part of this thesis, the impact of ship age on detention-related deficiencies was analyzed. The vessel age categories were broken into 6 categories based on 10-year age ranges. In the data set used, new vessels (<one-year-old) still show as 1-year old. Therefore, it is assumed that the range category for vessels aged "1-10 years" also includes select vessels that are less than 1 year old.

As shown in Figure 12, the average number of deficiencies per detention increased as the ship age increased across 2004-2017. This demonstrates that the older vessels that were detained had more deficiencies and therefore, needed additional resources to correct those deficiencies prior to release from detention.

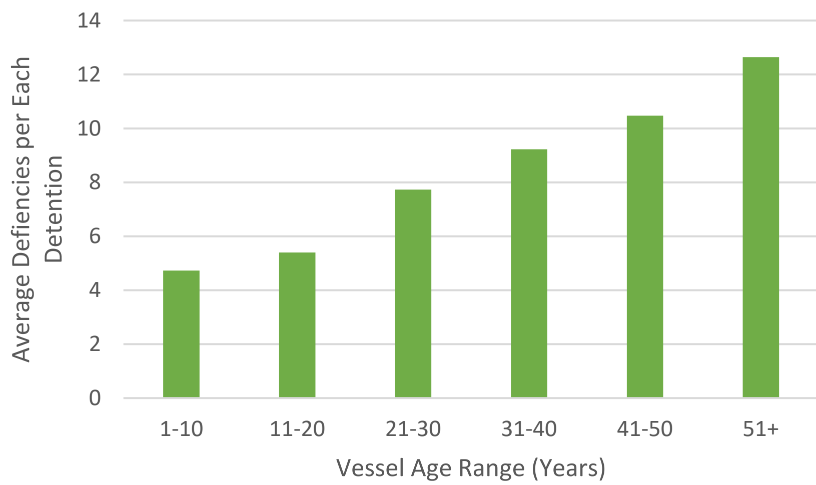


Figure 12. Average Deficiencies per Each Detention Based on Age Ranges (Data from 2004-2017)

The detention rate was calculated as the number of detained vessels divided by the total number of safety examinations in a given year and the deficiency rate was calculated as the number of detention-related deficiencies divided by the total number of safety examinations in a given year. One limitation of the data sets is that there is no data in regards to the number of safety examination per each age category, so the number of safety examinations are based on the year.

As shown in Figure 13, the 11-20 year and 31-40-year age categories had the highest rates of detentions per safety exam, and the 51+ age category had the lowest rate.

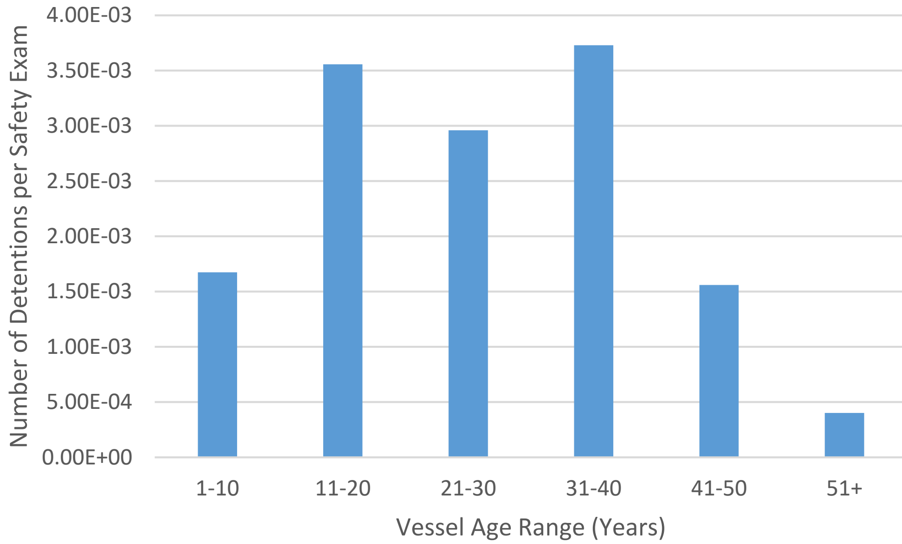


Figure 13. Detention Rate per Safety Examination Based on Age Categories (2004-2017)

In Figure 14, the deficiency rate per safety examination is shown based on age category.

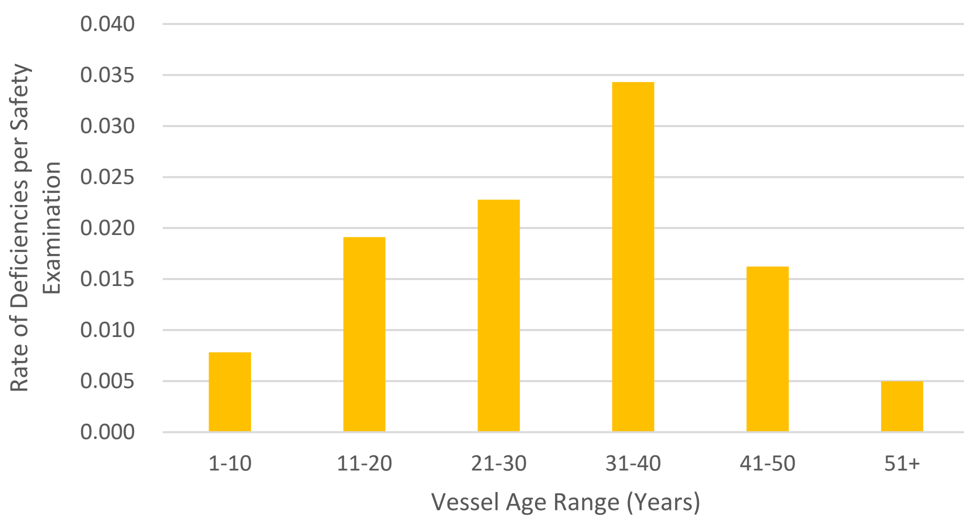


Figure 14. Deficiency Rate (Detention-Related) Per Safety Examination Divided by Age Category (2004-2017)

The 31-40-year age category had the highest deficiency rate (0.034) and the 51+ year age category had the lowest deficiency rate (0.0054). This demonstrates that although the older vessels (51+ age category) had more deficiencies occurring at each detention, the overall number of detentions and detention-related deficiencies is notably less per each safety examination than any other age category. In contrast, the 31-40-year age category had a distinctly higher rate of detentions and deficiencies. Postulating that this trend holds true for future vessels, this demonstrates that if a vessel is deemed to need a port state control safety examination in this age category (31-40 years old), it is more likely to result in a detention as opposed to another age category.

In dividing the detention-related deficiency data from 2004-2017 into age bins, the percentage of deficiencies for each system per each age bin were determined. For the age bin 1-10 years, Figure 15 shows that in this age bin, a majority of deficiencies were in Ops/Management system (24%). Additionally, 19% were in the Firefighting system, 14% were in the Documentation system, and 11% were in the Engineering system. Similarly, for the 11-20-year age bin, 22% deficiencies were in Operations/Management system, 15% were in the Firefighting system, 13% were in the Engineering system, and 13% were in the Documentation system. Figure 16 shows the TreeMap for this age bin.

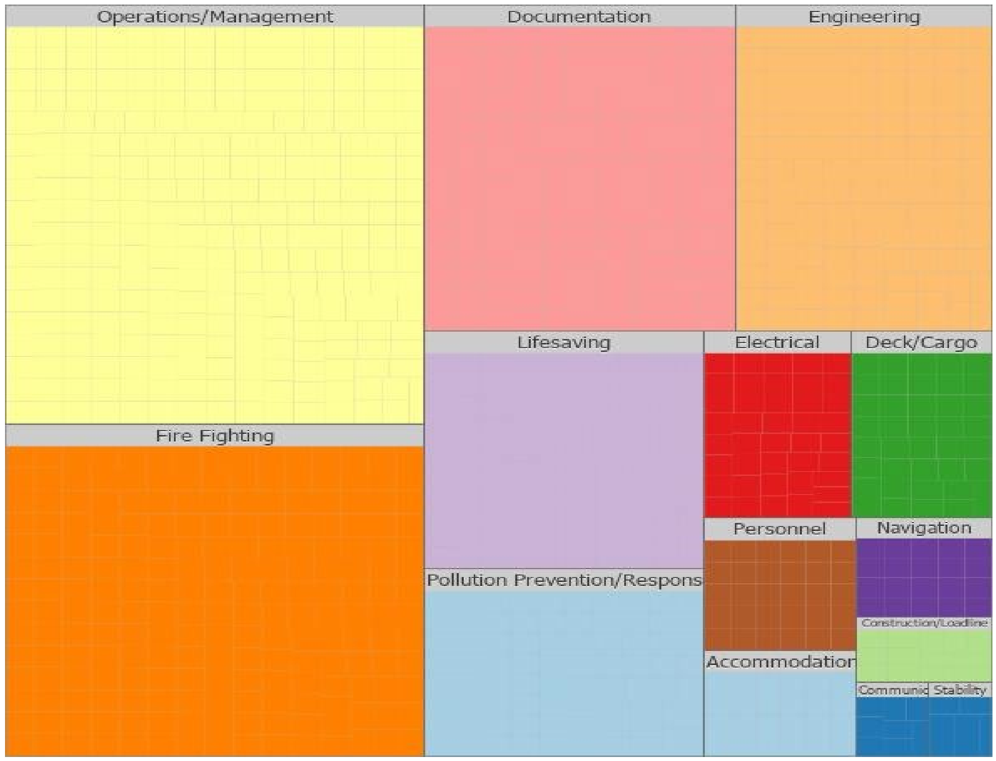


Figure 15. TreeMap of the Deficiency Systems in Age Bin 1-10 years

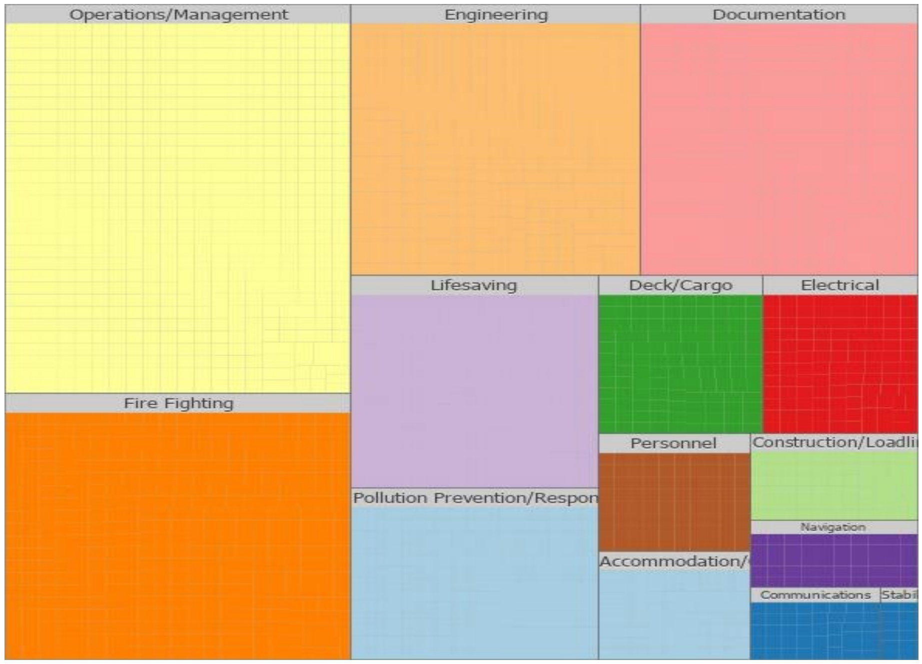


Figure 16. TreeMap of the Deficiency Systems in Age Bin 11-20 years

Although the 21-30-year age bin had the same top four systems in regards to deficiencies, there was a lesser percentage of Ops/Management system deficiencies (18%) and a greater percentage of Engineering system deficiencies (16%) when compared with the previous two age bins. Figure 17 represents this breakdown and also shows that 15% of deficiencies were from Firefighting system deficiencies and 10% were from Documentation system deficiencies.

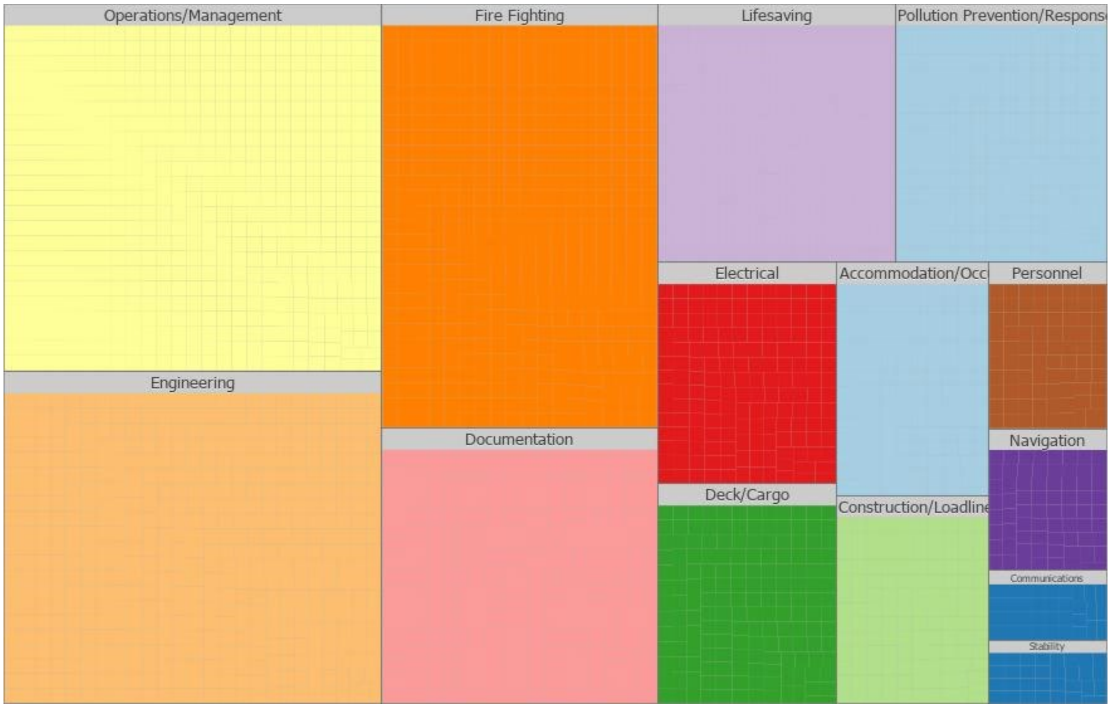


Figure 17. TreeMap of the Deficiency Systems in Age Bin 21-30 years

For the 31-40-year age bin, Operations/Management deficiencies made up 18% of all deficiencies, Engineering system deficiencies made up 15%, Firefighting system deficiencies made up 13%, and Documentation system deficiencies made up 10%. This is shown in Figure 18, and differs greatly from the 41-50-year age bin shown in Figure 19. The 41-50-year age bin had the following deficiency breakdown: 15% Documentation system deficiencies, 13% were Operations/Management deficiencies, 11% were Firefighting system deficiencies, and 11% were from Engineering system deficiencies.

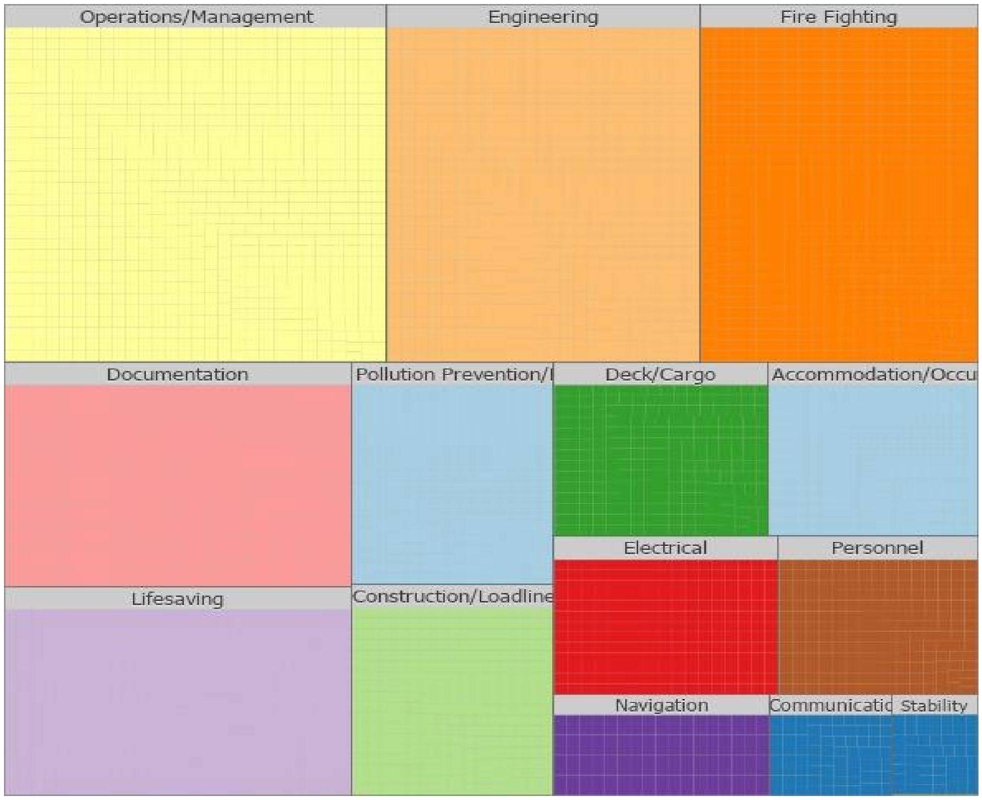


Figure 18. TreeMap of the Deficiency Systems in Age Bin 31-40 years

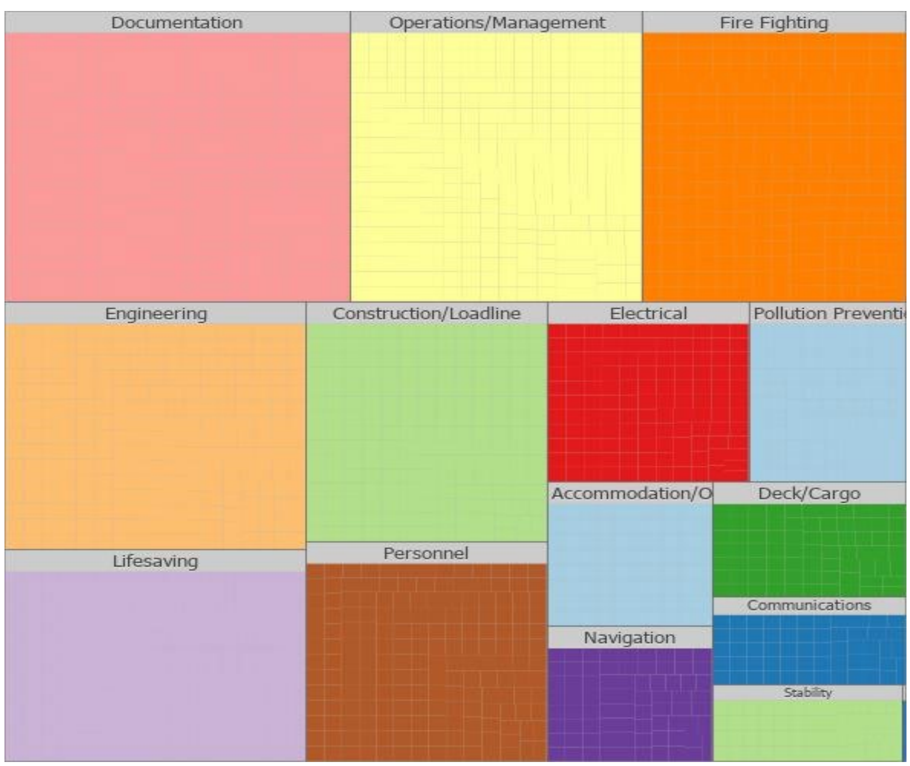


Figure 19. TreeMap of the Deficiency Systems in Age Bin 41-50 years

Differing greatly than any other age bin, the 51+ year age bin is comprised of 13% Operations/Management system deficiencies, 11% Construction/Loadline system deficiencies, 11% Documentation system deficiencies, and 10% Firefighting system deficiencies. Seen in Figure 20, this age bin is the only age range that has Construction/Loadline systems deficiencies in the top 4 systems. Based on my experience, this is due to the fact that vessels older than 51 years usually have hull or structural member deficiencies due to the ship's advanced age and the intense maintenance required on structural members is costly.

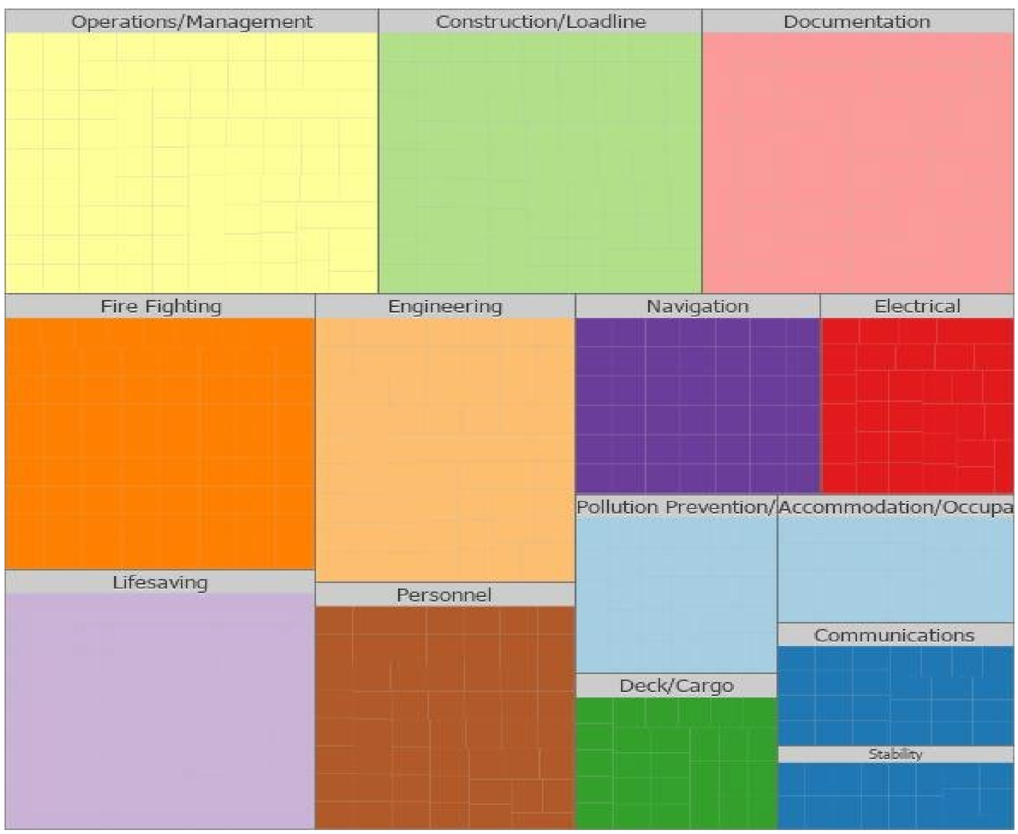


Figure 20. TreeMap of the Deficiency Systems in Age Bin 51+ year

To validate these age trends and to further examine the age trends with the respect to SMS detentions, a k-means cluster analysis was performed. This analysis showed that the age clusters were loosely defined from age 1-39 years and then from age 40-58 years. This could be partially explained due to the majority of SMS deficiencies occurred on vessels that were 39 years old, specifically in the Maintenance of Ship/Equipment SMS component category. After age 39, the number of SMS deficiencies related to detentions sharply decreases, especially in the Maintenance of Ship/Equipment component category.

Figure 21 shows a TreeMap of the SMS components for the age 1-39 bin based on the number of deficiencies in each component category. It can be seen that a majority (43%) of the SMS deficiencies that caused detentions, were due to the lack of maintenance to the vessel or equipment in this age range. The other top SMS deficiencies were Company Responsibility/Authority (10%), Master's Responsibility/Authority (8%), Safety/Environmental Policy (7%), and Documentation Maintenance/Control (7%).

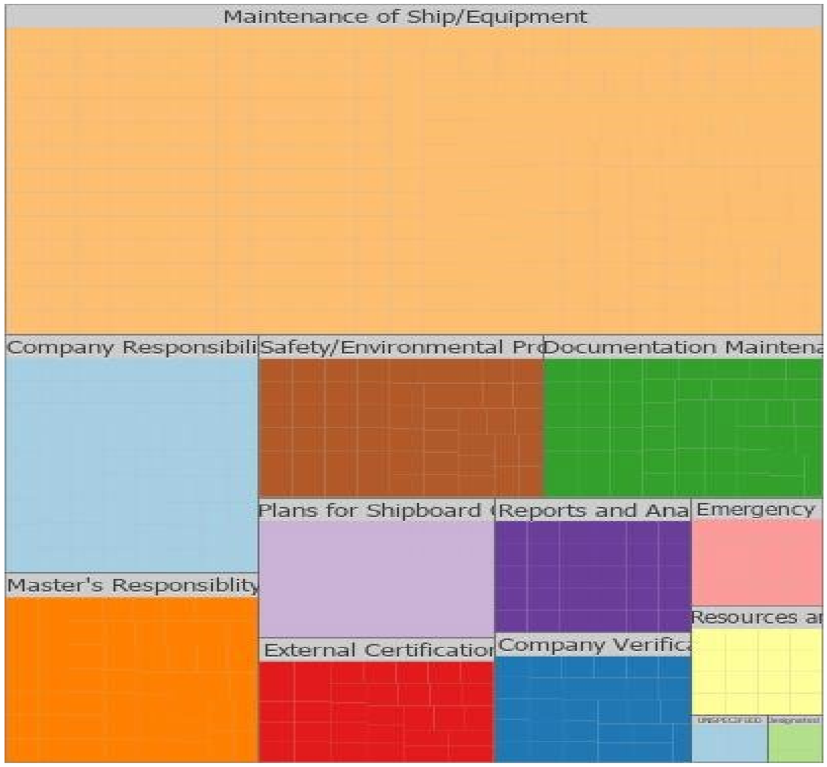


Figure 21. TreeMap of the SMS Deficiencies Segregated by Component Type for Vessels Aged 1-39

Figure 22 shows a TreeMap of the SMS components for the age 40-58 bin based on the number of deficiencies in each component category. In contrast to Figure 21, it can be seen that although the SMS deficiency that was the most frequent was still Maintenance of Ship/Equipment, it was drastically smaller percentage of the overall SMS deficiencies at 24%. In this age range, the other top SMS deficiencies also increased in percentage with both Company Responsibility/Authority and Master's Responsibility/Authority each making up 16% and External Certification/Verification/Control making up 10%.

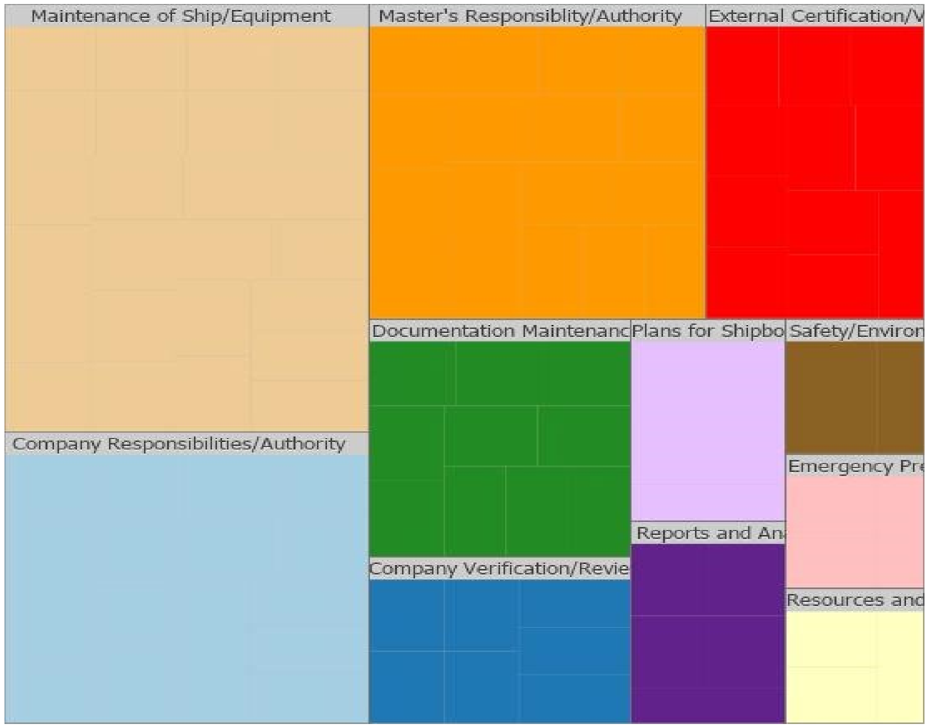


Figure 22. TreeMap of the SMS Deficiencies Segregated by Component Type for Vessels Aged 40-58

Section 4.4: Data Trends by Vessel Service

In the dataset, each vessel belongs to one of fourteen different vessel services based on ship design and cargo type. These are freight ship, tank ship, public freight, offshore supply vessel, passenger vessel, towing vessel, commercial fishing vessel, freight barge, recreational, industrial vessel, research vessel, mobile offshore drilling unit (MODU), and unspecified. As shown in the TreeMap in Figure 23, the two vessels with the most detention-related deficiencies were categorized as freight ships (77%) and tank ships (14%). This TreeMap is organized by Vessel Service type and the color is based on vessel service type. Lastly, the size of the blocks indicates the number of detention-related deficiencies for vessels in that service.

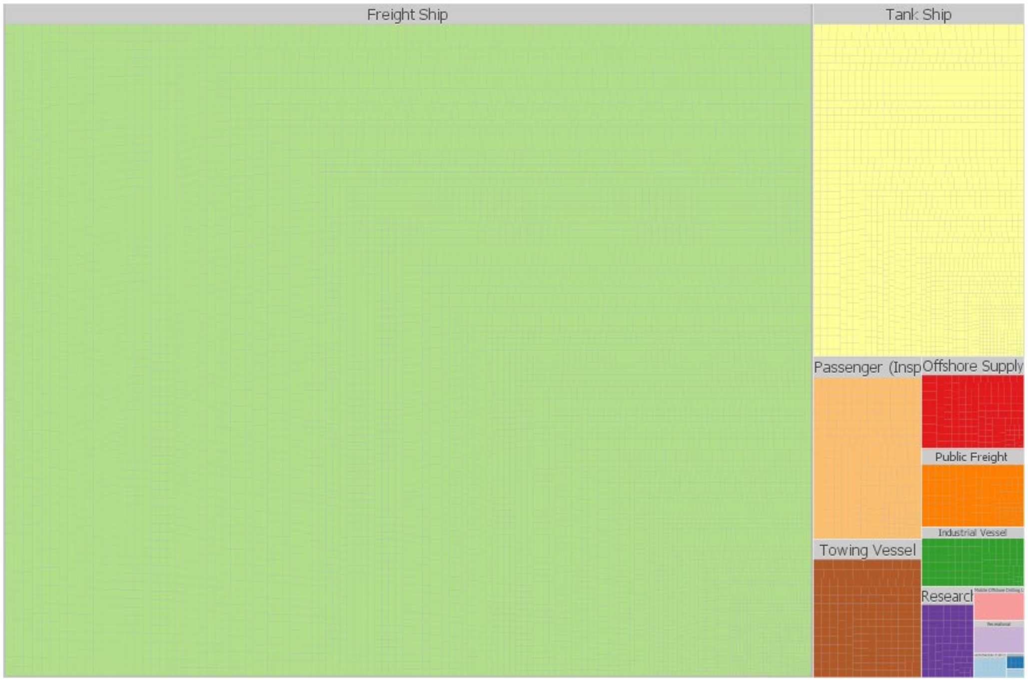


Figure 23. TreeMap of Vessel Service Types Organized by Detention-Related Deficiencies Occurring Most Frequently (2004-2017)

Figure 24 shows that from 2004 to 2017, 19% of all detentions involving freight ships included deficiencies in Operations and Management System. The other main system deficiencies for freight ship-detentions included Firefighting (14%), Engineering (15%), and Documentation (12%). Additionally, 16% of all tank ship detentions involved Operations/Management deficiencies. The additional major system deficiencies for tank ship-detentions are Deck/Cargo (16%), Firefighting (14%), and Engineering (11%).

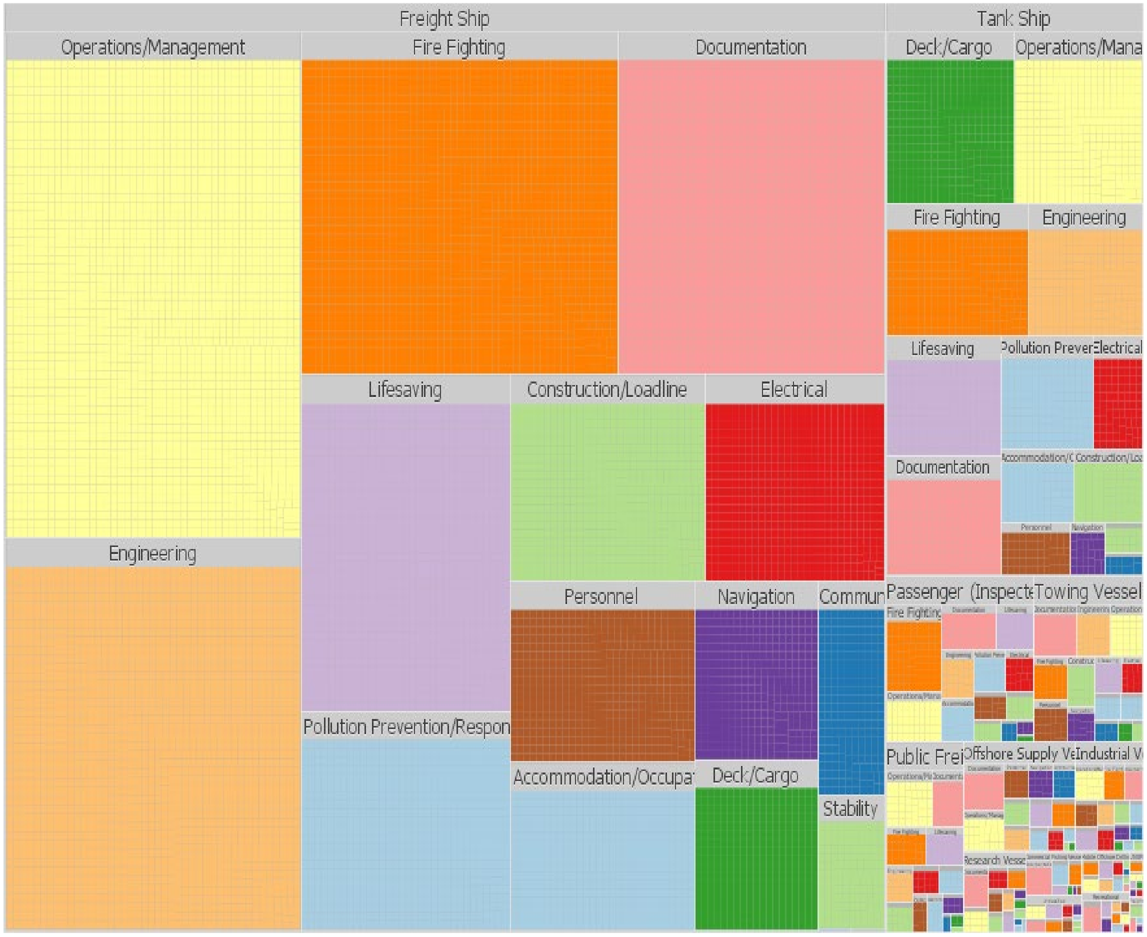


Figure 24. TreeMap of Vessel Service Types Organized by Deficient Systems Most Occurring (2004-2017)

In regards to tank ships, the deck/cargo and operations/management systems had an equal amount of deficiencies. This is concurrent with my experiences, since tank ships carry hazardous cargos, which have additional and more extensive safety regulations associated.

Chapter 5: Risk Analysis

Section 5.1: Defining Risk Analysis Framework

Subsection 5.1.1: Risk Analysis Model

The risk analysis model is defined as a Barrier BowTie Model, which has 8 main elements. These elements are the hazard, the top event, threats, consequences, preventive barriers, recovery barriers, escalation factors, and escalation factor barriers. These are further defined in Chapter 3, Section 3.3, Subsection 3.1.1. Figure 25 is an example of the Barrier BowTie Model created in BowTieXP software. It demonstrates the layout of the model elements.

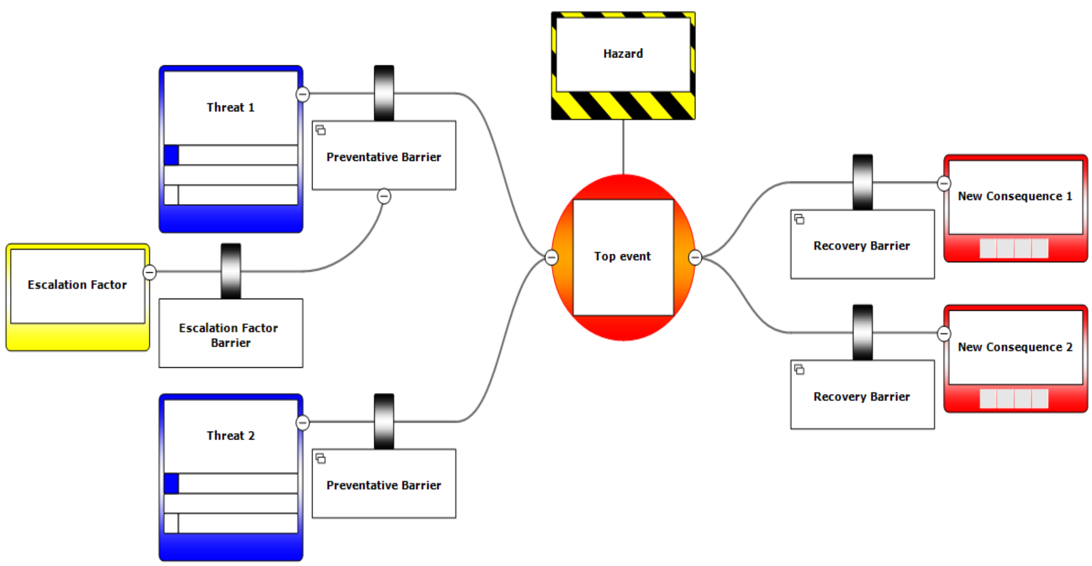


Figure 25. Example of Barrier BowTie Model

In Chapter 5, Sections 5.2 and 5.3 discuss the process of developing the Barrier BowTie Model and refer to portions of the completed Barrier BowTie Model. The completed Barrier BowTie model can be seen in its entirety in Appendix B. Section 5.4 discusses the implications of this model.

Subsection 5.1.2: Assumptions and Limitations

For the purposes of this thesis, there were specific assumptions made to complete the risk analysis and the limitations to the model set boundaries. The first assumption is that when the model refers to "a vessel" it is an internationally flagged vessel arriving into the United States that must comply with the international ISM Code standards. The second assumption is that the term "deficiency" is related to detention-related deficiencies. The third assumption for this model is that a vessel detention implies that a vessel failed to implement the vessel SMS. This is not true of all vessel detentions.

The first limitation is that due to time constraints, the risk analysis and model has not been validated by additional subject matter experts. The main information sources for development of this model are from my personal experiences in the U.S. Coast Guard, the literature review sources, and lastly from the data analysis in Chapter 4. The second limitation is that the Barrier BowTie Model software cannot incorporate the triggers identified during the Potential Problem Analysis portion of the risk analysis. They are listed separately in Section 5.3.3.

Section 5.2: Risk Analysis

Subsection 5.2.1: Hazard and Top Event Identification/Description

In accordance with IP Bank B.V. (2015)'s BowTie XP: Bowtie Methodology Manual, a hazard is the source of risk under a specific condition. The hazard for this risk analysis is an International Vessel Operating in U.S. Waters and requiring a U.S. Port State Control examination. The Top Event is defined as the event that changes the hazard's status from normal to abnormal. The top event for the risk analysis is a vessel detention, specifically one due to the failure to implement the vessel SMS onboard. There are other causes of vessel detentions, however, that is outside the scope of this thesis. Figure 26 shows the hazard and top event in the Barrier BowTie Model.

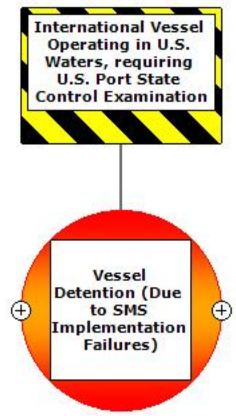


Figure 26. Hazard and Top Event in Barrier BowTie Model

Subsection 5.2.2: Identification of Threats and Consequences

Figure 27 shows the threats and consequences identified for this risk analysis. A substandard vessel is defined as "a ship whose hull, machinery, equipment, or operational safety is substantially below the standards required by the relevant convention" (Procedures for Port State Control, 2017). If a vessel is found to be substandard during a port state control examination, then the vessel is detained in the waters of that member state until the severe deficiency or deficiencies can be rectified. Therefore, all the threats, or causes of the top event, identified for this risk analysis are deficiencies related to the SMS that cause the vessel to be substandard and therefore detained.

The consequences are defined by I.P. Bank B.V. (2015) as the undesired events due to the top event. For this risk analysis, the consequences affect the following vessel stakeholders: Vessel Management Company, Vessel Owner, Vessel Crew/Master. The consequences of financial loss and loss of time are related to each other since a delay in schedule will cost the vessel owner and vessel operating company from increased port and docking fees or delays in offloading cargo which can result in penalties. However, there are financial losses to the vessel owner/management company from vessel detentions that are not related to the schedule loss. These include financial impacts due to correcting vessel deficiencies causing the vessel detention, as well as the financial impact of early crew turnover to replace crew members that may have contributed to the vessel detention. The consequences of loss of reputation and the financial loss to the vessel owner/management company are also related because the company will experience a loss of business due to the detention and therefore will have decreased revenues, especially in the short term. Lastly, the consequence of increased PSC examination frequency is partially related to the loss of time consequence since future PSC examinations can delay the vessel in future U.S. ports.

For further clarification, only one or more of the threats need to be present in order for the top event to occur. Likewise, not all the consequences list will occur if the top event occurs, but all the consequences could possibly occur.

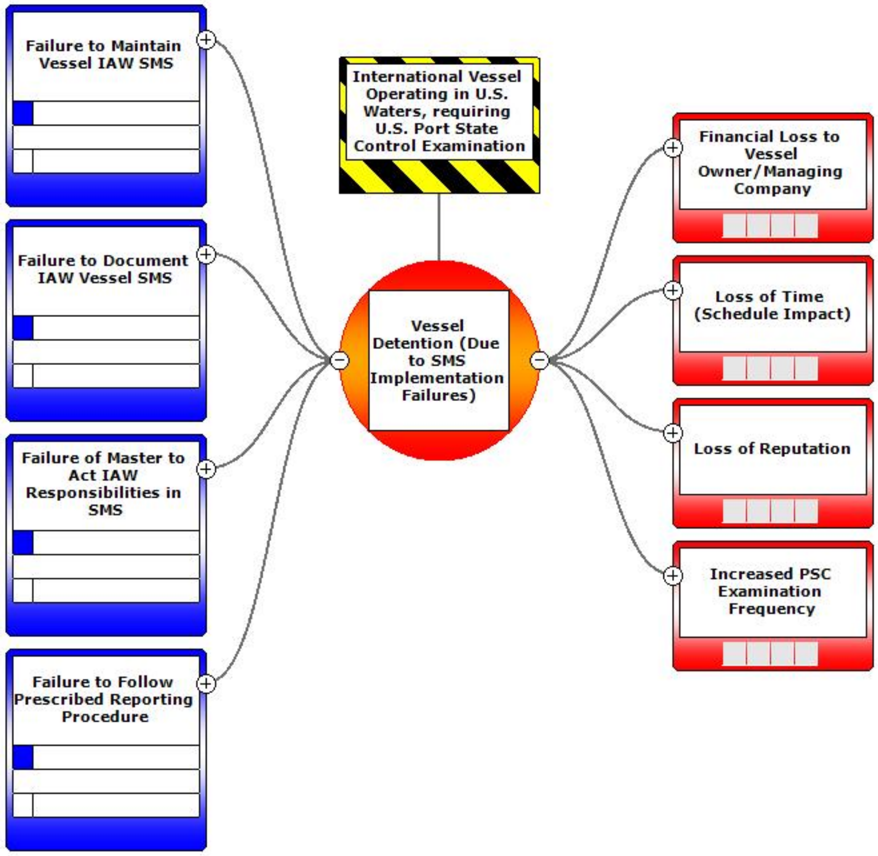


Figure 27. Threats and Consequences in Barrier BowTie Model

Section 5.3: Risk Management

Subsection 5.3.1: Preventive and Recovery Barrier Identification/Description

In accordance with the Barrier BowTie Methodology Manual (2015), the barriers are controls that either prevent or mitigate an event. Preventive barriers control or prevent the top event from occuring, whereas the recovery barriers mitigate the consequences resulting from the top event. If one or more of the preventive barriers fail, then the threat will cause the top event to occur. Likewise, if one or more of the recovery barriers fail, then the consequence is likely to occur due to lack of mititgation.

Figure 28 shows the preventive barriers. The preventive barriers were identified based on my personal experience in vessel inspections, as well as the insights from the research in Storkensen et al. (2017) and Lappalainen (2008). As mentioned in the Literature Review in Chapter 2, Storkensen et al. (2017) identified that there was a lack of critical thinking when it came to making safety-related decisions, such as which vessel systems/equipment to maintain and how to report safety incidents. They also mentioned that the complexity of SMSs contributed to the crew's lack of adherence. Therefore, preventive barriers would include training the crew regularly on the procedures within the SMS, conducting audits to ensure compliance, and overall simplifying the procedure through clarifying the requirements within the SMS. Lappalainen (2008) also mentioned lack of standard interpretation of the ISM Code and the complexities that exist within SMSs. Therefore, the preventive barrier of clarifying SMS procedures could prevent failures of a vessel's SMS.

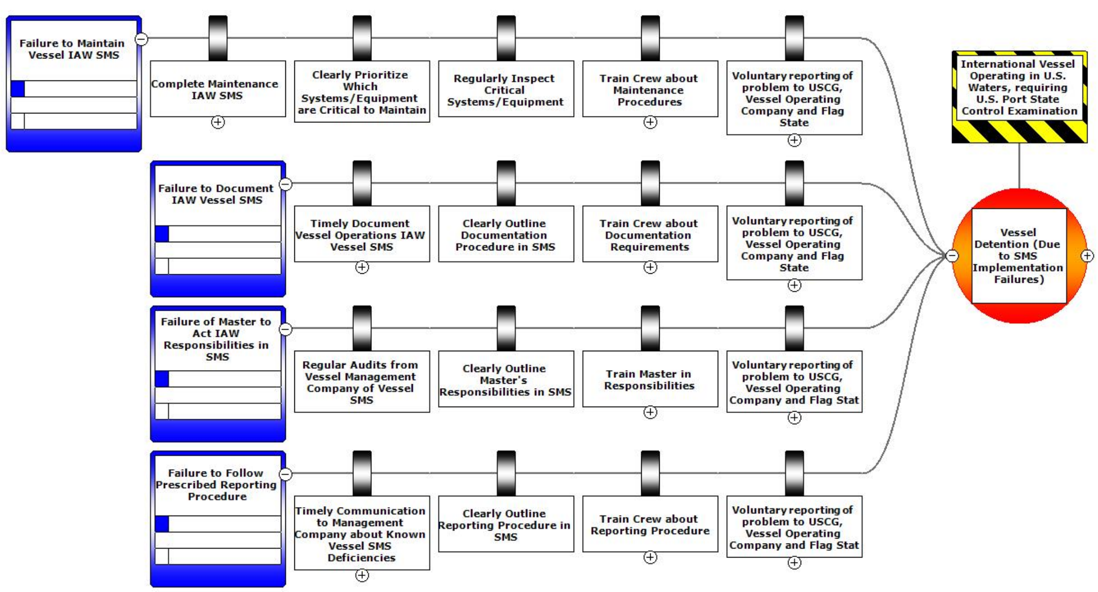


Figure 28. Preventive Barriers in Barrier BowTie Model (IAW: In accordance with)

Figure 29 shows the recovery barriers. The preventive barriers were identified based on my personal experience in port state control vessel inspections and Potential Problem Analysis. As seen in Subsection 3.3.2, the 5th step of Potential Problem Analysis includes defining measures to mitigate effects should the problem occur (Kepner and Tregoe, 1997). When looking at the top event as the problem or problem condition, these mitigation measures can be translated into preventive barriers.

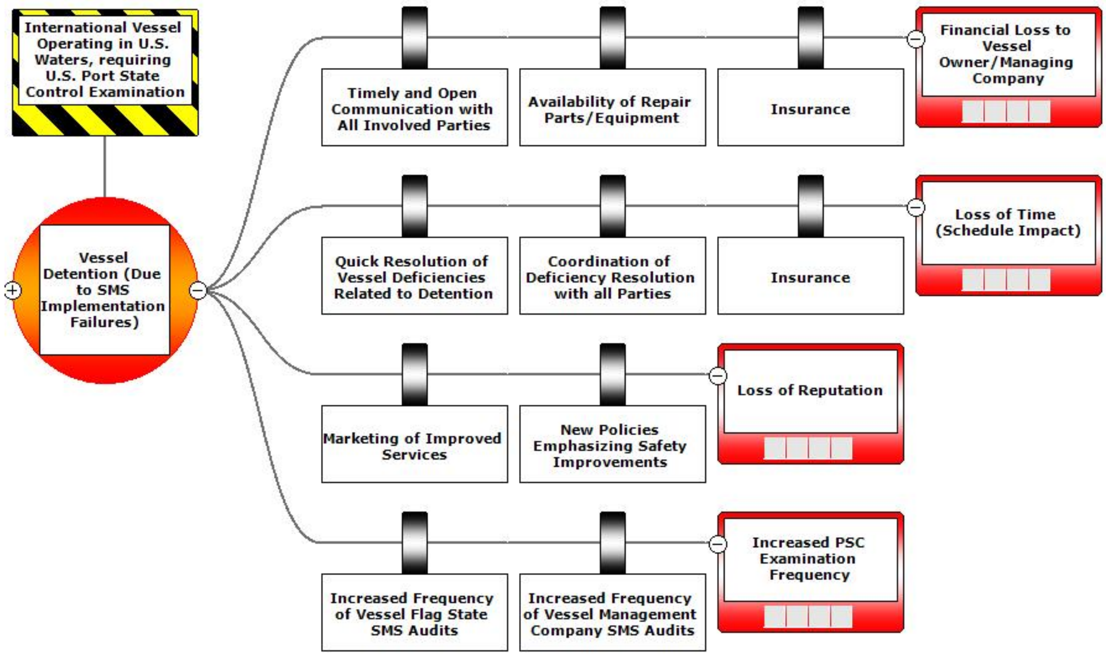


Figure 29. Recovery Barriers in Barrier BowTie Model

Subsection 5.3.2: Identification of Escalation Factors and Barriers

Escalation factors are those that cause the preventive or recovery factors to fail (IP Bank B.V., 2015). Escalation factors and their associated barriers for the preventive barriers are common to each threat and the first preventive barrier identified, which is to follow the SMS. Therefore, Figure 30 only shows the escalation factors and barriers for the threat, “Failure to Maintain Vessel” as a sample. The additionally escalation factors and barriers can be seen in Appendix B. The escalation factors and barriers were identified based on my personal experience in vessel inspections, as well as the insights from the research in Storkensen et al. (2017). As mentioned in the Literature Review in Chapter 2, Storkensen et al. (2017) identified crew complacency and complexity of the safety standards/SMS onboard as contributors to failing SMSs. Therefore, they are added escalation factors to the preventive barriers in Section 5.3.1.

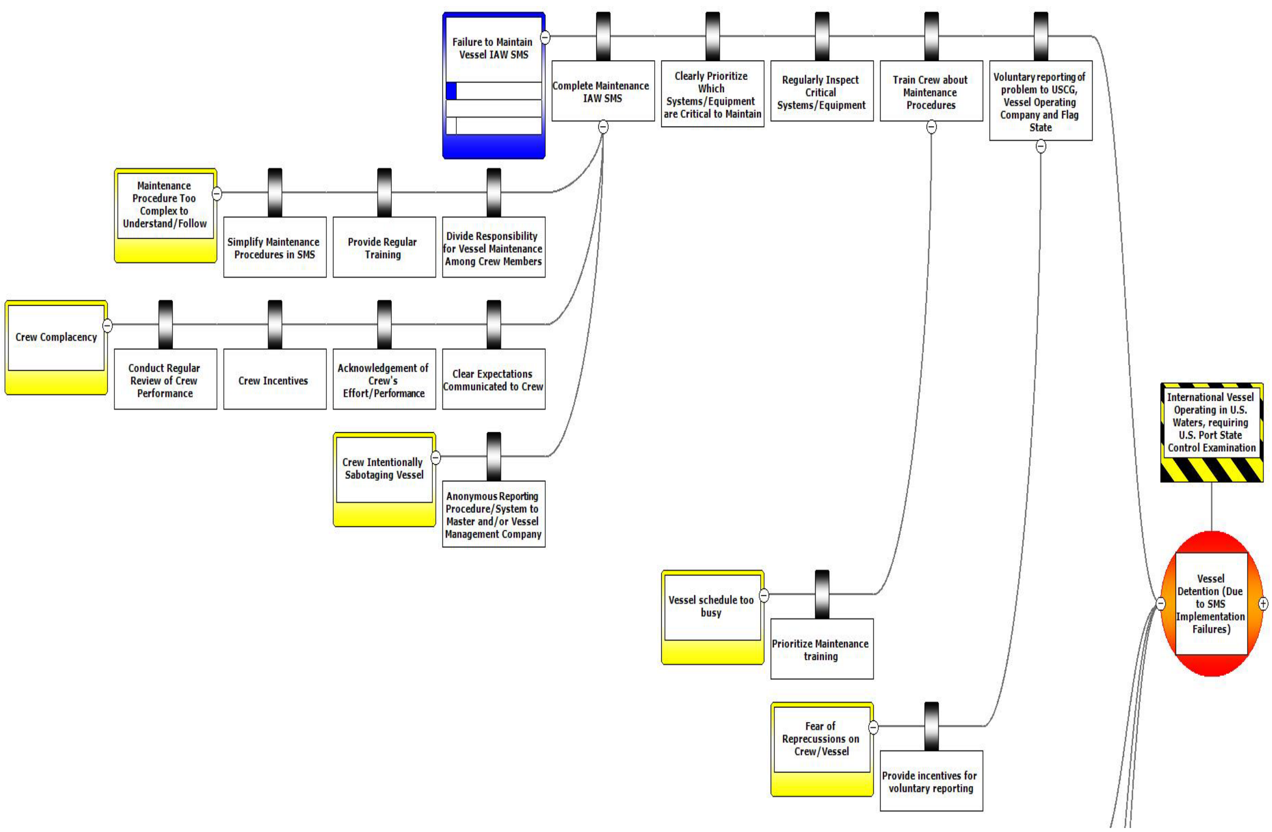


Figure 30. Sample of Escalation Factors and Barriers

Subsection 5.3.3: Identification of Triggers within the System

The last mitigation step in this thesis and in the potential problem analysis method is to identify triggers that can be placed or already exist within the system, which alert the stakeholders that the potential problem has occurred (Kepner and Tregoe, 1997). In this risk analysis, the potential problem is also defined as the top event, which is “vessel detention due to vessel SMS failures”. The only indicator that a vessel detention has occurred is that the port state control team has issued a detention. However, there are triggers that exist to indicate that there are failures with the vessel SMS. These triggers are part of auditing and port state control procedures prescribed in the ISM Code by the IMO. These triggers are not included in the model in Appendix B due to limitations in the model software. They are instead listed and described Table 3.

Table 3. Current Triggers Identifying Failures within Vessel SMS Implementation

Current Triggers	
Trigger	**Description**
Flag State (Classification Society) Audit	Regular (Annual) Audit of the Vessel SMS; issue letter of non-conformity or deficiencies for
Operating Management Company Review	Reviews SMS and issues new guidance on implementation; Issues corrective action plans if there is a deficiency or non-conformity
Crew Audit	Monthly Audits looking at different areas of SMS; correct deficiencies on the spot or create corrective action plan
U.S. Coast Guard Port State Control Examination	Examination of Documents/Certificates/Plans and vessel systems/equipment. Issue deficiencies and/or detention
Other Port State Control Examinations	Examination of Documents/Certificates/Plans and vessel systems/equipment. Issue deficiencies and/or detention

Section 5.4: Implications

As seen in Figure 9 (TreeMap) in Chapter 4, Section 4.2, Vessel Safety Management deficiencies were the leading cause of detentions from 2004-2017. When vessel SMS deficiencies were broken down to the component level in Figure 10, the failure to implement a SMS was frequently caused by a lack of maintenance of ship/equipment, the failure on the part of the master to take action based on his/her authority, the failure on part of the crew to document ship's operations, and the failure on the part of the company to take action based on their responsibility. In relation to the risk analysis in Chapter 5, the deficiency data reinforced which threats (causes) were occurring and leading to the top event, in this case vessel detentions. The threats in the Barrier BowTie Model in Figure 27 were validated by this data as well as my personal experience. This deficiency data in Chapter 4 also gave the relative frequency of occurrence for these threats and allowed for a prioritization in terms of areas to focus on for mitigation. This integration of deficiency data analysis and the Barrier BowTie Model can be used to develop additional risk analysis models for other top events related to vessel detentions, such as engineering-related detentions or documentation-related detentions.

Furthermore, the preventive barriers identified in Figure 28, are related to the SMS deficiency-categories in Figure 10 because those deficiency areas demonstrated where barriers were overcome. For example, the high occurrence of SMS deficiencies related to maintaining vessel equipment/systems identified in Figure 10, demonstrated that the threat of lack of maintenance has preventative barriers that were ineffective or able to be overcome. The other explanation for this high threat occurrence could also be due to the fact that the threat naturally occurs with such high frequency, since vessel maintenance is a costly and constant undertaking. The high frequency of one of the threats identified in Figure 27 could make threat mitigation more difficult due to higher costs associated with continuous mitigation. With the data of threat frequency and the Barrier BowTie model created in this thesis, a future next step could be to evaluate the strength and relative value of the different preventive barriers in Figure 28.

Chapter 6: Conclusion

Section 6.1: Summary of Findings

This thesis identified the causes of vessel detentions associated with vessel SMS implementation failures utilizing port state control deficiency data from 2004-2017. Chapter 4, Section 4.1, detailed the context and descriptive statistics of vessel arrivals into the U.S., the port state control examinations performed, and the detentions that occurred. It was discovered that the number of unique vessels arriving into the U.S. has been increasing from 2004-2017, whereas the number of port state control safety examinations have been slowly decreasing. On the other hand, the number of detentions in the U.S. varied narrowly year-to-year with an average of 142/year from 2004-2017. Of the detentions that occurred during this timeframe, a majority of them were caused by Operations/Management deficiencies onboard the vessels as shown in Section 4.2. Vessel Safety Management deficiencies made up 34% of all Operations/Management deficiencies and were the most frequently occurring. Furthermore, it was discovered through the data analysis that the top four causes of SMS-related detentions were the failure to maintain the vessel's equipment/systems, failure of the vessel's master to act in accordance with his responsibilities, failure to appropriately document vessel operations, and failure to report in accordance with (IAW) vessel SMS (company responsibility/authority). The relationship between the port state control deficiency data in Chapter 4 and risk analysis in Chapter 5 was established through these identified causes of vessel SMS failures. These causes informed the threat assessment in the Barrier BowTie Model in Chapter 5, Section 5.2.2.

In Sections 4.3 and 4.4., the data analysis showed that there are differing trends in the causes of detentions and the causes of SMS detentions based on vessel age and vessel service types. It was identified in this thesis that for vessels aged 1-40 years and those that were 51 years or older, operations & management system deficiencies were the leading cause of detentions from 2004-2017, with the leading deficiency subsystem being vessel SMS implementation failures. However, for vessel that were aged 41-50 years, documentation deficiencies were the leading cause of detentions.

Additionally, the cluster analysis in Section 4.3 demonstrated that for SMS detention-related deficiencies, the deficiency trends clustered from ages 1-39 years and from ages 40-58 years based on the SMS deficiency component. Although in both age bins the majority of SMS detentions were caused by the lack of maintenance on the vessel or equipment, vessels aged 1-39 years had nearly double the percentage of total SMS deficiencies in this category. Furthermore, for vessels aged 40-58 years, there was an increased percentage of SMS deficiencies related to external certification when compared with the vessels aged 1-39. These results demonstrated there is a critical shift in SMS detention causes after a vessel exceeds 39 years old.

Section 4.4 demonstrated that the deficiencies from freight vessels and tank vessels made up 90% of all detention-related deficiencies from 2004-2017. As expected, Operations/Management system deficiencies made up a majority of deficiencies for both service types. However, tank vessels did have nearly as many

Deck/Cargo detention-related deficiencies due to the hazardous nature of the cargo onboard, which increased the detention risk due to cargo. The variations based on vessel age and vessel service uncovered in thesis, highlight the previously unexplored importance of these two factors when analyzing the risks and frequency of threats (causes) associated with vessel detentions.

The Barrier BowTie and Potential Problem Analysis risk analysis methods were integrated successfully in Chapter 5, which created a more in-depth risk assessment than one method alone could have provided. Following the Potential Problem Analysis steps, the Barrier BowTie Model was created following the integrated procedure in Section 3.3.4. This risk mitigation strategies created in Chapter 5, Section 5.3 included preventive barriers, recovery barriers, escalation barriers, and the triggers. The subdivision of these mitigation strategies allowed for the risk analysis to address and mitigate various aspects of risk related to the top event of vessel detentions due to vessel SMS implementation failures. The preventive barriers in Figure 28 demonstrated the mitigation strategies that should be used to prevent the causes (threats) of the top event. The recovery barriers in Figure 29 showed the mitigation areas that could be used to reduce or eliminate the consequences related to vessel detentions. The escalation barriers in Figure 30 identified that mitigation strategies for preventing the escalation factors related to the weaknesses of the preventive barriers. The triggers identified in Table 3 were procedures already in place that allow for identification of vessel SMS failures prior to the top event taking place. Each of these barriers, whether individually or collectively applied to their respective mitigation area, and the identified triggers formed the complete risk mitigation analysis to the main problem of vessel SMS implementation failures, which led to detentions.

Section 6.2: Recommendations

As identified in the risk analysis in Figure 28, there are several preventive barriers, one or more of which could prevent a threat from causing a vessel detention. An additional preventive barrier that is recommended to prevent the threat of "Failure of Master to Act IAW Responsibilities in SMS" is an anonymous feedback system. This would be used by the crew to report vessel safety problems to the vessel management company and/or the flag state authority (or appointed classification society). This recommendation was also suggested by Lappalainen (2008). He identified that crew members often faced the fear of reprisal if they reported problems to their supervisor, usually the Chief Officer or the Chief Engineer, or to the vessel master. This assessment coincides with my own personal experience, which taught me that although most of the time the master of the vessel prioritizes safety onboard, there are some masters that are motivated by other things. These include complacency, greed due to financial incentives from a lack of safety problems while they are onboard, or fear of reprisal themselves. Crew members in these safety-compromised situations occasionally sought other methods of reporting, such as whistleblowing to port state control officers. However, if unsubstantiated or if the master or other crew learned of the crew members' report, there would often be reprisal. Therefore, an anonymous feedback system would provide a balance between the crew's desire for a safe vessel and the master's control over the crew's reference for future work and their quality of life while on the ship.

The safety feedback system that I recommend should be both anonymous and voluntary, and each crew member should have equal access to it. In the aviation community, the Aviation Safety Reporting System (ASRS) exists to allow any member, at any level, of the aviation industry to file a safety report. As seen on the ASRS website, this data is used to correct safety problems that require immediate attention, to collect and analyze safety data to inform policy, and to decrease the potential for aviation accidents (Aviation Safety Reporting System, 2019). There are two ways to report using this system to include online and through the mail. The anonymous safety feedback system that I am proposing should include at a minimum these two methods of reporting to allow for maximum anonymity and accessibility.

One of the challenges to implementing this feedback system is the ownership and creation of this system. I propose that the ownership and creation of the feedback system would be best handled by the IMO and then implemented by the individual flag states who are signatory to the IMO. This would allow for better uniformity of reports and safety data received through a central online reporting platform and standard reporting forms. It would also allow the IMO, as well as the flag states, to collect this safety data for incorporation into safety bulletins and future safety regulations/standards.

Additionally, it is recommended that the USCG and the IMO adopt the data-informed risk analysis method carried out in this thesis to assess and update vessel safety management standards. In the short term, these organizations can assess updates to the safety management system standards based on the threats and barriers identified in Chapter 5. Through additional evaluation of the preventive barriers and escalation factors/barriers using additional port state control data, the IMO and/or USCG can further understand the additional ways that regulations and additional policies can be used mitigate the risk of vessel detentions from SMS deficiencies.

Furthermore, based on the risk analysis, it is recommended that vessel management companies and owners review and perform additional evaluations of the threats, preventive barriers, and escalation factors/barriers. This would allow these stakeholders to create effective strategies to better implement SMS onboard their vessel through understanding the most common causes of failure. One of the most common barriers across each of the threats is to reduce the complexity of the SMS to make it easier to implement onboard. Therefore, it is recommended that each vessel management company review the complexity of the SMS onboard their vessels. This can be done through verbally testing the master and crew on their knowledge of the SMS. Additionally, it is recommended that an evaluation of recovery barriers be performed to understand better ways to reduce the effects of vessel detentions when they do occur and allow for contingency plans to be put in place prior to a vessel detention.

Section 6.3: Contributions

As demonstrated in this thesis, the integration of a systems engineering view of the safety management system and risk analysis can provide new insights into the SMS as a whole and show how SMS implementation can be improved onboard international vessels. The deficiency and detention data analysis in Chapter 4 provided a foundation for the risk analysis in Chapter 5, and identified the priority of which SMS components to focus on for both the risk analysis and for vessel stakeholders. Moreover, Chapter 4 involved a unique study of the factors of vessel age and vessel service and demonstrated that variations in the detention causes exist based on these factors. These two factors have not been a focus of vessel safety management and vessel detention literature in the past. The variations based on vessel age and vessel service uncovered in this thesis, highlight the previously understated importance of these two factors when analyzing the risks and frequency of threats (causes) associated with vessel detentions. Moreover, the cluster analysis showed a shift in the causes of SMS detentions after a vessel ages 39 years. This knowledge can be used by stakeholders to address unique risks regarding vessel SMS implementation based on the age of the vessel, as well as the vessel service type. This can be accomplished through specific policies from the Flag States, USCG, IMO, and/or vessel management companies. Also, this knowledge can update the training given to masters and crew members regarding challenges to SMS implementation based on the specific age and vessel service areas.

Furthermore, this thesis utilized vessel detention data analysis and the integration of the Barrier BowTie and Potential Problem Analysis risk assessment methods to provide an innovative view into vessel safety management failures, which can assist vessel stakeholders. With the knowledge of the causes and barriers of detentions related to vessel SMS failures, stakeholders, mainly vessel management companies, vessel crews, and vessel owners, can identify potential areas of improvement for vessel safety management system implementation. Furthermore, stakeholders can utilize this deficiency data and the risk analyses to better understand and evaluate the barriers that are in place to order to prevent vessel SMS detentions from occurring in the future. Moreover, they can utilize the additional mitigation strategies of the recovery barriers, the escalation barriers, and the triggers to both identify a vessel SMS failure has occurred and to mitigate the effects. This knowledge can be used to focus efforts on strengthening or implementing new barriers through the identification of gaps within a company's SMS implementation. This could reduce the potential for threat occurrence with the goal of reducing vessel detentions overall, which would reduce the burden on U.S. and international port state control programs.

Moreover, this data and risk analyses in this thesis can be used by the IMO and other maritime regulating authorities (Flag and Port states) to understand the principal causes of vessel detentions and the variations based on vessel age and service, as well as the effectiveness of barriers to prevent detentions. This can be useful in developing specific regulations or international standards that enforce the strengthening of barrier effectiveness, as well as increase the barriers intended to mitigate the potential consequences should a detention occur.

Lastly, the technique applied in this thesis and relationship drawn between deficiency data analysis and Barrier BowTie/Potential Problem risk analysis can be applied to other transportation systems, specifically those that have safety management systems already regulated by law or in practice through industrial policy. In the United States, the main transportation systems include aviation, transit (bus) systems, and rail systems. Although detentions are solely utilized in the international maritime community, aviation, bus and rail systems each have a similar mechanism for halting operations due to safety-related failures. The techniques in this thesis can be applied to these safety mechanisms to analyze risks of safety failures using historic data. Unlike rail and transit systems, the Federal Aviation Administration (FAA) currently implements a continuous data-informed risk analysis method for safety management as part of the aviation SMS program. As seen on the FAA website, the main difference between their risk analysis methodology and this thesis' methodology is that there is no subdivision among the various control measures (barriers) as there is in the Barrier BowTie method. There is also no identification of triggers that identify when safety failures occur (Federal Aviation Administration, 2019). Therefore, this techniques in this thesis could be analyzed by the FAA with the intention of incorporating additional risk analysis techniques to improve the risk analysis and overall aviation safety management system program.

Section 6.4: Limitations

The limitations of this thesis are distributed among the data set, the data analysis, the risk analysis approach, and the risk analysis itself. First, the data set collected for the data analysis in Chapter 4 was exclusively from U.S. Coast Guard Port State databases and therefore does not include additional port state examination data from other countries. This means that the data analysis does not encompass all the vessel detentions and deficiencies across the international maritime community. Instead, it used the data from USCG sources as a sample population of all international maritime vessels. Furthermore, the data analysis in Chapter 4 was exploratory in nature. Due to the size of the data collected and the focus of this thesis, the data analysis was limited to the areas of vessel detentions, related deficiencies, and to the factors of vessel age and vessel service. Additionally, these factors were unable to be analyzed further due to time constraints and the defined scope of this thesis.

The limitations of the Barrier BowTie Model were first in the method itself and then with the software used. As described in Section 2.2, this threats, barriers, and consequences identified in this thesis have dependencies that could not be distinguished in the model. Additionally, the BowTieXP software used to create the model makes the barriers look like they must all fail in order to cause the top event, escalation factor, or consequence. However, this is not the case as failure of one or more barriers could cause the undesired effect. Lastly, the software is limited in the integration of Potential Problem Analysis as it could not incorporate the triggers identified.

Finally, the risk analysis model was not validated by additional subject matter experts due to time constraints. The model was solely informed based on the data analysis, the literature review, and my personal experiences as a marine inspector for the U.S. Coast Guard.

Section 6.5: Future work

Although beyond the scope of this thesis, the data related to vessel age and vessel service should be further analyzed to study the variations in vessel detention causes based on these factors. This additional analysis could lead to the development of a collection of more specific Barrier BowTie Models that focus on vessels of different age and vessel service categories. Work in this area could serve to inform stakeholders of more specific threats based on their particular fleet of vessels. For example, if a vessel management company managed only tank vessels, a Barrier BowTie Model informed with data only relating to tank vessel detentions and deficiencies, would give a more detailed and accurate risk analysis and mitigation strategies. Likewise, if a vessel owner has only vessels that are older than 40 years old, a Barrier BowTie Model might reveal different risk mitigation strategies than if that vessel owner owned vessels younger than 40 years old.

Another area of further research is the analysis of the barriers identified in Chapter 5.3. This future analysis could be used to study the effectiveness (or ineffectiveness) of different preventive, recovery, and escalation barriers and the causes of barrier failure. Moreover, research into quantifying the relative frequency of the threats as well as the relative value of the barriers would help inform this analysis. This could further assist stakeholders in resource allocation in order to best prevent SMS failures and vessel detentions.

Lastly, as mentioned in Section 6.2, another area of future work is through application of the safety failure data analysis and risk analysis (Barrier BowTie and Potential Problem Analysis integration) in different transportation areas. As the FAA already uses a data informed risk analysis in their safety management system, it is recommended that the methods used in this thesis be applied to transportation systems that do not already have risk analysis incorporated into their safety management system or practices. The two transportation areas within the United States that could benefit most from this research are the federal transit system and the federal rail system. Both transportation areas lack structured and data-informed risk analysis as well as a systematic view of safety management. Through the application of the techniques used in this thesis to include historic safety data analysis and risk analysis, the stakeholders in these industries could benefit by understanding further causes of safety failures and the development of targeted mitigation strategies.

Appendix A: List of Systems and Subsystems

System	Subsystem
Accommodation/Occupational Safety	Cooking System
	Heating
	Medical/First Aid
	Messroom
	Occupational Safety
	Other Accommodation Spaces
	Portable Water System
	Refrigeration (air conditioning)
	Refrigeration (stores)
	Sleeping Accommodations
	Ventilation
	Washroom/Toilet
Communications	Alarms/Indicators
	Audible Communications
	Automatic Identification System (AIS)
	Internal Communications System
	Long Range Identification and Tracking (LRIT)
	Public Address System
	Radio Communications
	Security
	Visual Communication
Construction/Loadline	Hull
	Markings
	Penetrations
	Structures
Deck/Cargo	Ballast
	Cargo Condition
	Cargo Heating
	Cargo Refrigeration
	Cargo Stowage
	Cargo Transfer (Solid)
	Cargo Transfer/Lightering (Liquid)
	Crude Oil Washing System
	Holds/Tanks
	Inert Gas System
	Marine Portable Tanks
	Mooring/Anchoring
	Towing
	Vapor Control Systems

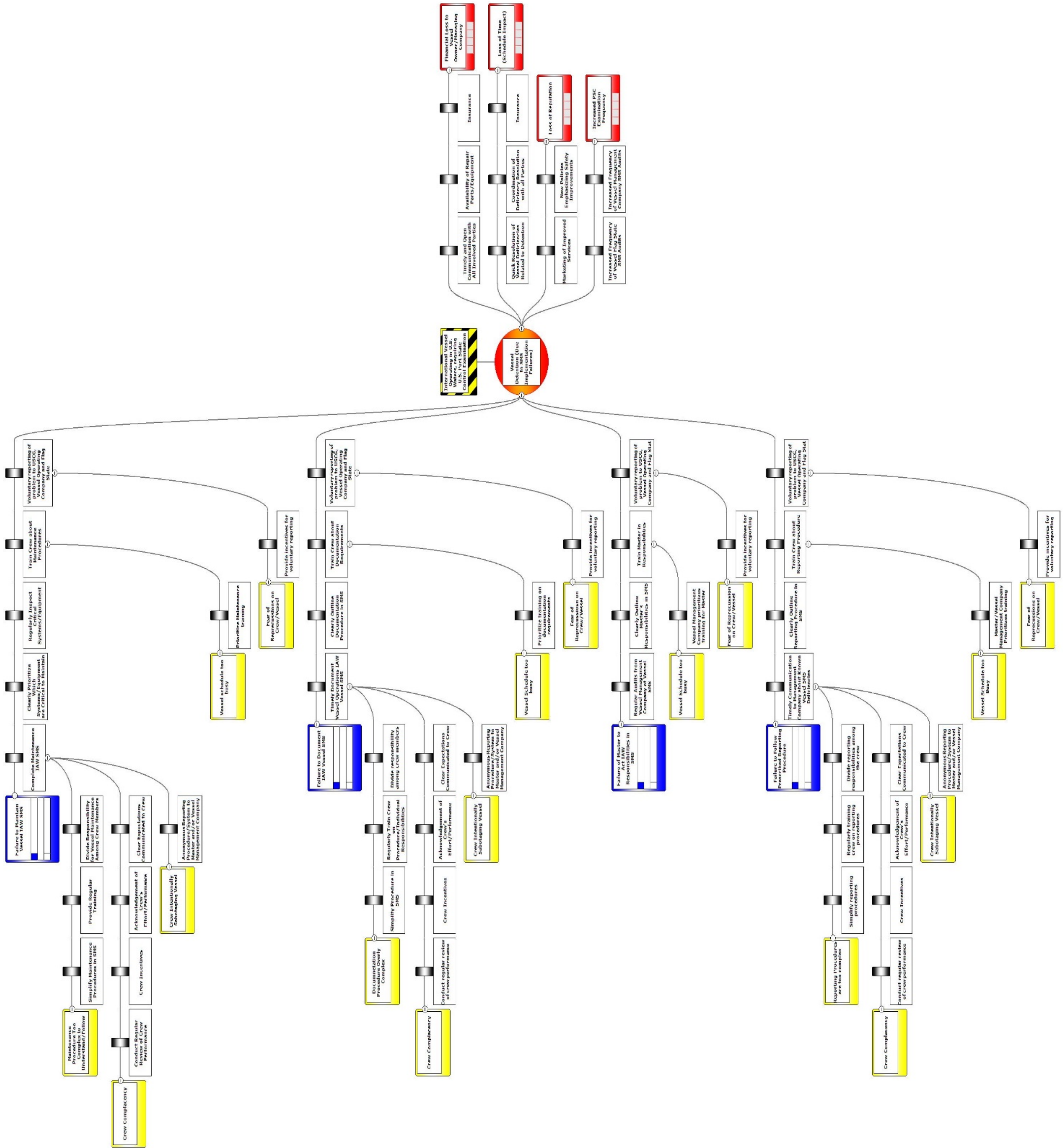
Documentation	Certificates/Documents
	Logs/Records
	Manifest/Lists
	Manuals/Policy Documentation
	Markings/Placards
	Safety Management System
	Safety/Response Plans/Programs
	Security Plan/Alternate Security Program
Electrical	Electric Generation Source (emergency)
	Electric Generation Source (service)
	Lighting (emergency)
	Lighting (Service)
Engineering	Bilge Water Management System
	Compressed Air System (start air)
	Diesel Engine (auxiliary)
	Diesel Engine (propulsion-direct drive)
	Diesel Engine (propulsion-electric)
	Diesel Engine (propulsion-reduction gear)
	Electric Propulsion System
	Engine Controls (Electric/Electronic)
	Feedwater/Condensate Water System
	Freshwater Generation System
	Freshwater System (Air cooling)
	Freshwater System (cylinder head cooling)
	Freshwater System (Injector cooling)
	Freshwater system (intermediary cooling)
	Freshwater System (jacket water cooling)
	Freshwater System (piston cooling)
	Fuel Oil Service System
	Fuel Oil Storage/Transfer System
	Gasoline Engine (auxiliary)
	Gasoline Engine (propulsion)
	Generator (propulsion/auxiliary-electric)
	Generator (Propulsion-electric)
	Lubricating Oil Service System
	Lubricating Oil Storage/Transfer System
	Non-conventional Propulsion/Steering
	Pressure Vessel
	Reduction Gearing/Clutches
	Sea-water system (primary cooling)
	Shafting/Propeller Arrangements
	Steam Boiler (auxiliary/waste heat)

	Steam System (auxiliary)
	Steam System (main)
	Steam Turbine
	Steering Gear System
	Thrusters
Firefighting	Automatic Sprinkler System
	Combustible Materials
	Emergency Fire Pumps
	Fire Bucket
	Fire Hoses
	Fire Hydrants
	Fire Main
	Fire Pumps
	Fireman's Outfit
	Fixed CO2 Fire Extinguishing System
	Fixed Deck Foam System
	Fixed Fire Detection System
	Fixed Gas Fire Extinguishing System
	Fixed Halon Fire Extinguishing System
	Fixed High-Expansion Foam Fire Extinguishing System
	Fixed Low-Expansion Foam Fire Extinguishing System
	Fixed Pressure Water-Spraying Fire Extinguishing System
	Fixed Steam Fire Extinguishing System
	Grease Extraction Hood
	International Shore Connection
	Means of Escape
	Miscellaneous Items
	Nozzles
	Portable CO2 Fire Extinguisher
	Portable Dry Chemical Fire Extinguisher
	Portable Foam Applicators
	Remote Fuel Shutoffs
	Self-contained Breathing Apparatus
	Semi-portable Chemical Foam Fire Extinguishers
	Semi-portable CO2 Fire Extinguishers
	Structural-A Class Divisions
	Structural-B Class Divisions
	Structural-C Class Divisions
	Structural-Horizontal Zones
	Structural-Main Vertical Zones
	Structural Fire Protection-General

	Ventilation Systems
	Water Fog Applicators
Lifesaving	Buoyant Apparatus
	Buoyant Smoke Signals
	Embarkation Appliances/Stations
	Emergency Outfit
	Hand Flares
	Immersion Suits
	Inflatable Buoyant Apparatus
	Inflatable Liferafts
	Launching Appliances
	Lifeboat
	Lifeboat Equipment
	Lifebuoys
	Lifejacket/PFD (General)
	Lifejacket/PFD (Type I)
	Lifejacket/PFD (Type II)
	Lifejacket/PFD (Type III)
	Lifejacket/PFD (Type IV)
	Lifejacket/PFD (Type V)
	Liferaft Equipment
	Line-Throwing Appliances
	Rescue Boat
	Rescue Boat Equipment
	Rigid Liferafts
	Rocket Parachute Flares
	Thermal Protective Aids
	Visual Distress Signals (General)
Navigation	Collision/Grounding Avoidance
	Electronic Positioning
	Emergency Steering
	Piloting/Steering
	Voyage Data Recorder
Operations/Management	Ballast Water Management
	Bilge/Bilge System Management
	Cargo Transfer/Lightering
	Casualty Reporting/Post Casualty Actions
	Drills/Instruction
	Drug and Alcohol Testing
	EPA Vessel General Permit (VGP)
	Equipment Service/Testing
	Lifesaving

	Logs/Records
	Mandatory Ship Reporting Systems
	Navigation Safety
	Pollution
	Ports/Waterways Safety
	Security
	Vessel Safety Management
Personnel	Certificates/Documents/Licenses
	Manning/Qualifications
	Training
Pollution Prevention/Response	Prevention Equipment
	Response Equipment
Sail Rigging	Winches
Stability	Freeing Ports
	Incline Test
	Intact Righting Energy
	Intact Stability
	Unintentional Flooding
	Water on Deck
	Watertight Integrity
	Weathertight Integrity

Appendix B: Completed Barrier BowTie Model



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