Exploring the Relationship Between Accumulated Departures from Specifications and Associated Casualties and Mishaps

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Dedication

The author wishes to acknowledge the love and support he received from his family. This journey was long, difficult and many times I questioned the sanity of my decision to undertake this effort. Yet in every instance I received love, encouragement and a friendly reminder of my persistent nature. Therefore, this is dedicated to you!
Acknowledgments

The author wishes to acknowledge the Holy Trinity who was all called upon during this journey at various times, and gratefully, I received what I needed when I needed it.

The author also wishes to acknowledge the numerous people who helped throughout this journey. And while there is always a danger in naming folks as I may inadvertently leave someone out, the following deserve special acknowledgment: Mr. Dan Ahern, Ms. Kate Brock, Mr. Douglas Vaughters and especially Dr. Vesely.

Microsoft® Project 2010, JMP® Version 12 and IBM® SPSS® Statistics Version 25 was used as a reference to investigate and analyze portions of the dataset.
Abstract of Praxis

Exploring the Relationship Between Accumulated Departures from Specifications and Associated Casualties and Mishaps

The Systems Engineering community spends considerable effort developing system specifications during the design phase. Yet during the operational and support phase, there is a potential degradation of those specifications in the form of delayed, missed, or insufficient maintenance (i.e., maintenance that does not restore the system to the design specifications), which are commonly called departures (e.g., Structure/Weld Joint - Incorrect Electrode Usage, Valve Timing, etc.). While the impact of each departure on the system is reviewed as part of the current approval process, there is no evaluation to the equipment and/or personnel from the accumulated number of departures.

The impact of these accumulated departures is analyzed to determine if there is a correlation between these accumulated departures and casualties to equipment (documented on casualty reports that impact system availability and operational readiness) and/or mishaps to document a safety event and/or damage to property. The analysis required the development of a framework to systematically store and catalog U.S. Navy data on a select set of hulls from 2004 to 2016 specifically addressing data on 6,810 departures, 4,808 casualty reports, and 6 mishaps. A series of analyses were conducted to include (1) ensuring the hulls met the criteria of in-service (i.e., operational ready for deployment), (2) test for trends together as a class followed by this same analysis on a per hull basis, which helped define the correct correlation method, (3) Spearman’s rank-order correlation analyses as a class followed by this same analysis on a
per hull basis and (4) regression analysis to determine if departures could be used to predict future casualties. The correlations and regression results suggested meaningful, statistically significant at the 0.01 level, for a majority of the relationships between the accumulated number of departures determined at the class level and for each individual hull. The framework and process that is described in this paper can be used to track and influence the number of casualty reports that are predicted to occur by controlling the number of accumulated departure from specifications. There also was no correlation determined between the accumulated departures from specifications and subsequent Mishaps and thus there was no regression analysis conducted.
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### Glossary of Terms

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<th>Full Form</th>
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<tr>
<td>CASREP</td>
<td>Casualty Reports</td>
</tr>
<tr>
<td>CAT</td>
<td>Category</td>
</tr>
<tr>
<td>DFS</td>
<td>Departures from Specifications</td>
</tr>
<tr>
<td>DOD</td>
<td>Department of Defense</td>
</tr>
<tr>
<td>DOE</td>
<td>Department of Energy</td>
</tr>
<tr>
<td>HRA</td>
<td>Hazard and Risk Assessment</td>
</tr>
<tr>
<td>INCOSE</td>
<td>International Council on Systems Engineering</td>
</tr>
<tr>
<td>ISO</td>
<td>International Standards Organization</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>O/O&amp;S</td>
<td>Operations/Operations and Support</td>
</tr>
<tr>
<td>PMS</td>
<td>Preventive Maintenance System</td>
</tr>
<tr>
<td>PSA</td>
<td>Post Shakedown Availability</td>
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<tr>
<td>SUBSAFE</td>
<td>Submarine Safety</td>
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Chapter 1 - Introduction

1.1 Background

The science of safety consists of many different approaches. One example of a strategic approach to manage safety, as discussed by Glendon A.I. & Stanton N.A. (2000), is to start with a Business Strategy which includes a Risk Management Strategy which encompasses the Safety Management Systems and at a lower tier Risk Assessment and Control. This original research paper will address a portion of Risk Assessment and Control by specifically addressing the cumulative effects of Departures from Specifications (DFSs) by developing a framework. A DFS is fully defined in Chapter 2.

During the Life Cycle of a System, the customer’s expectations for the system are transitioned into a set of requirements, commonly referred to as the system specification which is a part of the technical baseline. These requirements are then used to develop and produce a hardware or software solution that satisfies the customer’s expectations. The generation of the solution can take many years and is called many different things as the International Council on Systems Engineering (INCOSE) (2015) defines it: Industry (e.g., Study and Implementation Periods, etc.) and Government (e.g., U.S. Department of Energy [DOE] Project Planning Period & Project Execution, U.S. National Aeronautics and Space Administration [NASA] Pre-Phase A through Phase D, U.S. Department of Defense [DoD] Pre-Milestone A through Post Milestone C/Initial Operating Capability, etc.). Upon exiting the Development and Production Periods, the system enters service which is also known as the Operations Period (Industry) or the Operations and Support Period (DoD) (International Council on Systems Engineering (INCOSE), 2015).
System specifications are the cornerstone of the technical baseline of any Acquisition Program. There has been a great deal of research already accomplished on the development and management of the system specification utilizing good systems engineering practices during the development and production periods as evident in the amount of information dedicated to these phases in such publications as the Systems Engineering Handbook (International Council on Systems Engineering (INCOSE)) and the Guide to the Systems Engineering Body of Knowledge (BKCASE Editorial Board, 2016). However, there has been lesser attention paid to the system specifications during the Operations/Operations and Support (O/O&S) Period. This paper will address this last period of the life cycle or just prior to retirement and disposal of the system. The objective of this research is to develop a systematic framework to evaluate the relationship between DFSs, subsequent casualties (i.e., equipment failure with mission impact) and mishaps (i.e., safety event and/or damage to property) during the operational and support phase (International Council on Systems Engineering (INCOSE), 2015).

1.2 Problem Statement

The Departures from Specifications (DFSs) are not being adequately addressed with respect to risk as they are reviewed in isolation from previously approved DFSs which can have disastrous consequences.

1.3 Thesis Statement

The analysis of the accumulated DFSs to casualties to equipment (documented on casualty reports) or mishaps (documenting a safety event and/or damage to property) will predict future casualties or mishaps.
1.4 Research Objectives

The impact of departures, specifically accumulated departures, will be determined to see if there is:

- a correlation between these accumulated departures and casualties to equipment and/or mishaps to document a safety event and/or damage to property, and
- if accumulated departures can be used as a precursor.

This will increase the risk knowledge level available to the risk analyst and subsequently decrease the uncertainty.

1.5 Research Questions

1. Is there a way to increase the risk knowledge during the operations and support phase of the lifecycle by investigating the relationship between Departures from Specifications which are controllable and Casualties and/or Mishaps which are risk associated?

2. Is there a way to control risk by predicting Casualties and/or Mishaps?

1.6 Research Hypotheses

There are two main Research Hypotheses:

1. H1a: There is a relationship between cum Departure from Specifications and Combined (CAT 2, 3, and 4) Casualties and/or Combined Mishaps (Class A, B, C, D, and H).
   - H1a(1): There is a relationship between Combined Major and Minor Departure from Specifications and Combined Casualties and/or Mishaps
• H1a(2): There is a relationship between Major Departure from Specifications and Combined Casualties and/or Mishaps.

• H1a(3): There is a relationship between Minor Departure from Specifications and Combined Casualties and/or Mishaps.

2. H2a: The accumulation of DFSs is a predictor of future Casualties and/or Mishaps.

1.7 Research Limitations

The Research Limitations, also already stated, is limited to the O/O&S Period of the system life cycle. Although the granting of DFSs and the occurrence of casualties/incidents happen in many industries and Government organizations, U.S. Navy information for twelve (12) similar hulls (hull is defined as a ship) that were delivered by the shipbuilder to the U.S. Navy during the period selected for analysis, which is from delivery of the hull until December 2016, are used. One exception occurs with Hull 3’s period lasting only until May 2015 due to it entering an extended maintenance availability at that time. An explanation of each data type and the quality checks used are covered in the subsequent subsections to include if the twelve hulls met the criteria for being in-service (i.e., representative of hulls during the operational and support phase and no longer in the warranty period of the shipbuilder).

For the 12 hulls used as part of this research, an analysis was conducted on the quality of the data. One potential issue could be inconsistent reporting of mishaps, casualties, and DFSs. While mishaps are generally written, as the writing of them is enforced by an outside agency, the Navy Safety Center, a review of the data has determined Casualty Reports (CASREPs) are not written in each instance based on a qualitative analysis of the
dataset. There are several reasons why this may be the case to include (1) too many CASREPs being written could be viewed as a negative reflection on the crew, (2) if repair parts are onboard the equipment is repaired and not reported through the CASREP system, and (3) there is no forcing function to write a CASREP. These impact the ability to learn from the failure of the equipment from one hull to another. DFSs also are not consistently written from hull to hull for the same condition, as evident when the system analysis of ship control was completed. In addition, there is inconsistent use on what is captured by a DFS as some are global in nature such as material issues that affect multiple systems are captured on one DFS and other DFSs are part specific. One should be able to call up any system and get a listing of all DFSs (e.g., Archived, Active and even maybe Canceled). Kyriakidis et al. (2012) found similar challenges with data accuracy and unreliability in their study on Metro railway safety.

An additional limitation was not all of the information contained within a DFS could be used as an increase in the amount of information that was used would result in a classified analysis.

1.8 Organization of Praxis

The Praxis is organized as follows, Chapter 2 contains a Literature Review as it pertains to this research, Chapter 3 is a discuss on the Methodology used in the analysis, Chapter 4 contains the Results of the analysis, and Chapter 5 is broken into 4 sections with the first section, entitled Discussion, containing an interpretation of the results. The three remaining sections of Chapter 5 contain a discussion on what are the Conclusions of this research, what are the Contributions to the greater engineering management

5
community from the research, and where follow-on research could go in the last section entitled *Future Directions*. 
Chapter 2 – Literature Review

There are many journal articles on the Lifecycle Engineering part of the American Society of Mechanical Engineers engineering management knowledge domain of Strategic Planning and Change Management (American Society of Mechanical Engineers, 2010). These include literature on system safety which includes risk management. However, there is a gap in the literature when it comes to discussing departures from specifications and their relation to casualties and mishaps. As a result, the following chapter starts with an overview of the importance of systems engineering management followed by some historical examples that impacted system safety. This is then followed by a discussion on the literature associated with the risk management portion of system safety where the definitions of Departures from Specifications, Casualties, and Mishaps are captured. Resilience engineering is introduced next with the chapter concluding with a short discussion on how a well-intentioned organization can become complacent and drift into failure.

Systems engineering and systems engineering management methodologies play a large role in the operation of complex engineering systems (Franke, 2001). Maintaining a consistent level of performance over the life-cycle of any system, especially a complex system, is recognized as a challenge from an engineering perspective and yet it is the expectation of the customer (Sols et al., 2013). Within the DoD, the customer is the system’s program office that is responsible for managing all aspects of the system to include the system safety process throughout the life-cycle of the system (Department of Defense, 2012). It is the engineering part of the program office that accomplishes a large
part of this effort which includes the consideration of any changes (e.g., interfaces, users, hardware, and software).

Two major events changed the approach to system safety: (1) On April 10, 1963, the USS THRESHER was lost at sea with all hands while conducting sea trials following a maintenance availability. 129 people died as a result. The 1964 report by the Joint Committee on Atomic Energy cited the U.S. Navy’s Court of Inquiry determination that a loss of seawater from a piping system was most likely the cause and the loss of seawater probably affected electrical circuits and caused a loss of power. The loss of seawater from a piping system was not an unknown scenario as it was determined during the investigation into the disaster that it was possible specifications were waived or departed from during the USS THRESHER’s service life (Joint Committee on Atomic Energy, 1964). (2) On February 1, 2003, Space Shuttle Columbia was destroyed as it was reentering the earth’s atmosphere. All seven astronauts were lost as a result. As the Columbia Accident Investigation Board (Reid et al., 2003) pointed out, foam from the external tank striking the shuttle during liftoff and causing damage, was known and accepted as an out of specification [italics added] condition. However, it was underappreciated according to (Benjamin et al., 2016).

System safety was changed after the loss of the USS THRESHER with the start of the U.S. Navy’s Submarine Safety Program, also known as SUBSAFE, and the loss of the Columbia Space Shuttle resulted in NASA and Navy benchmarking safety efforts and has been the study of extensive safety research over the last 15 years. Several authors (Madsen and Desai, 2010; Mouraa et al., 2017) researched into how organizations learn from past mistakes adds credibility that organizations do learn from past failures but
further research by Desai (2010) indicates that this learning varies. Several studies (Kim and Miner, 2007; Madsen, 2009) state that organizations also learn vicariously from failures or near failures of others as NASA demonstrated in their benchmarking efforts with the U.S. Navy. Each of these examples is of a complex system and each had a known component failure that interacted with another component in an unintended way which led to the loss of the overall system. It is this unintended interaction of components that are difficult to understand which is why safety needs to be viewed at the system level (Leveson, 2011). DoD and NASA, along with the airline industry and the oil and gas industry, develop, produce and operate some of the most complex systems ever made by humans and system safety must continue to evolve.

Risk management, specifically analysis, is a part of system safety as it helps to support the decision-making process. There is a need to view risk management throughout a project’s lifecycle and the importance to recognize the different needs change throughout the seasons a project experiences (Nielsen, 2006). Eight categories of project specific risk factors were developed by Nielsen (2006) with the delivery/operation risk factor being the most pertinent one for this research as it pertains to design, production and operation of the system or to state it another way, the life-cycle of a system. While Nielsen wrote about the importance of the seasons of a project, Altablakh et al. (2013) discuss two categories of risk assessment techniques; product and process. They state product assessment techniques include Failure Mode and Effect Analysis (FMEA) and Risk in Early Design (RED) and go on to state process assessment techniques include such things as Layer of Protection Analysis (LOPA) and the Swiss Cheese Model (SCM). Several authors (Aven and Kristensen, 2005; Aven and Ylönen,
2016) state that complex systems cannot be managed in the traditional perspective of risk analysis as they are probability focused for estimating risk and they then make a conclusion based on this approach on whether the risk is acceptable. Rundmo and Nordfj (2017) cite several studies that show how safety experts look more at the Probability [P] portion of the risk equation while lay people focus on the Consequence [C] portion. Aven (2012) discusses the historical content of risk from the first use of the word “risk” in the mid-12th century to the concept of risk and its evolution from probability based approach (i.e., Probability of an event and the Consequence if the event occurred) to the new way of thinking where “uncertainty” needs to be addressed which is based on some of his earlier research (Aven, 2011a, 2011b, 2010; Aven and Zio, 2011). There is more on this new way of thinking at the end of this chapter.

The Systems Engineering community is well known for introducing rigor and discipline into defining and understanding a program’s requirements during the acquisition portion or the early stages of the system lifecycle (United States Government Accountability Office, 2016). However, Amalbertib et al. (2003) recognized once a system is operational, which accounts for 60% of the total DoD system costs, according to the Defense Acquisition University (2017), the external pressures to keep the system operating often can cause the system to migrate to and operate in conditions that are outside of the designers’ original specifications or expectations. Such conditions, when they are known, are captured in many different forms throughout industry, and the terminology normally associated with these occurrences is “deviations” or “waivers” (COMUSFLTFORCOM, 2015; Federal Aviation Administration, 2017; NASA, 2016;
World Health Organization, 2013). Table 1 contains a sample of definitions for these terms.

<table>
<thead>
<tr>
<th>Organization</th>
<th>Definition</th>
</tr>
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<tbody>
<tr>
<td><strong>U.S. Federal Aviation Administration (FAA)</strong></td>
<td>A deviation is “when a regulatory section contains phrases such as ‘unless otherwise authorized by the Administrator,’ ‘the Administrator may,’ ‘if the Administrator finds,’ ‘the Administrator may authorize,’ ‘the Administrator allows a deviation,’ ‘notwithstanding the Administrator may issue operations specifications,’ or other similar wording, the regulatory flexibility is referred to as a deviation (Federal Aviation Administration, 2017).” A waiver is “when the regulatory section contains phrases such as ‘the Administrator may issue a certificate of waiver,’ ‘in accordance with the terms of a certificate of waiver issued by the Administrator,’ or other similar wording, the regulatory flexibility is referred to as a waiver (Federal Aviation Administration, 2017).”</td>
</tr>
<tr>
<td><strong>U.S. Navy</strong></td>
<td>A deviation is a request before the work is started.</td>
</tr>
<tr>
<td></td>
<td>A waiver is requested after the work has been completed.</td>
</tr>
<tr>
<td></td>
<td>A Departure from Specification (DFS) captures both deviations and waivers and is used to identify a lack of compliance with plans, procedures, instructions, or authoritative documents during a maintenance action or operations (COMUSFLTFORCOM, 2015)[COMUSFLTFORCOM, 2015] (Note: The oldest use of the term DFSs for the U.S. Navy is from (“General specifications for machinery for vessels of the United States Navy covering work under cognizance of Bureau of Steam Engineering,” 1920).</td>
</tr>
<tr>
<td><strong>NASA</strong></td>
<td>The terminology of a waiver is also used by (NASA, 2016) and they go even further when they clearly define granting of waivers as a Risk Acceptance decision.</td>
</tr>
<tr>
<td><strong>World Health Organization (WHO)</strong></td>
<td>The terminology of a deviation is also used by the World Health Organization (WHO) when it comes to manufacturing of vaccines (World Health Organization, 2013). Below are their definitions:</td>
</tr>
<tr>
<td></td>
<td>Minor Deviations are when the deviation does not affect any quality attribute, a critical process parameter, or an equipment or instrument critical for process or control.</td>
</tr>
</tbody>
</table>
Major Deviations are when the deviation affects a quality attribute, a critical process parameter, an equipment or instrument critical for process or control, of which the impact to patients (or personnel/environment) is unlikely.

Critical Deviation is when the deviation affects a quality attribute, a critical process parameter, an equipment or instrument critical for process or control, of which the impact to patients (or personnel or environment) is highly probable, including life-threatening situations.

In many cases, these deviations or waivers are granted with no explicit evaluation of the risk impacts (NASA, 2016; NAVSEA, 2015). In cases where deviations or waivers are granted with an accompanying risk indication, the risk assessment for that deviation or waiver is done on an individual basis with no evaluation of the risk impact of cumulative departures granted to date that still remain(s) in effect (NASA, 2016; NAVSEA, 2011). There are many references on risk management and risk of mishaps throughout Systems Engineering literature (Commandant of the Marine Corps, 2014; Commander Naval Sea Systems Command et al., 2008; Department of Defense, 2012; Department of the Army, 2007; Federal Aviation Administration, 2000; ISO, 2009; Leitch, 2010; U.S. Navy Safety Center, 2018) but very few evaluating the risk impacts of departures and none on cumulative departures (NASA, 2016; NAVSEA, 2011).

Leveson (2011) states during operations of a system, safety is achieved or maintained partly by the design of the system and partly by the effective control of the system during operations. In high-reliability industries, as accidents happen only in extremely rare occurrences, Morrow et al. (2014) state, “less significant events that occur more frequently are relied upon as indicators of potentially degrading performance.” Keeping systems safe to operate is a challenge as the failure of one part, and the techniques used in that analysis, are not always sufficient when you study the entire system according to
(Aven and Kristensen, 2005; Aven and Zio, 2011; Bjerga et al., 2016) and (Leveson, 2011). And according to the *(COLUMBIA ACCIDENT INVESTIGATION BOARD (CAIB), 2003)* “…complex systems almost always fail in complex ways.”

An engineering firm’s way to accomplish effective and efficient life-cycle management, given the challenges associated with complex systems, is to use data-driven analytics. Data-driven analytics allow for the identification of trends and patterns to all for better informed decisions. Data-driven decision-making enables informed decisions by revealing hidden insights which minimizes risks, especially in complex contexts (Naderpajouh et al., 2016) and has the added benefit to change well entrenched opinions on critical features in engineering design by showing objectively that the technology is nearing or going to be used outside the engineering safety range (Matricciani, 2001).

Thus, the understanding of complex systems can be improved, when some components are not meeting system specifications, by considering management of DFSs, which is not possible without an effective framework, and the relationship between the accumulation of various DFSs and the number of Casualties (which are documented in Casualty Reports [CASREPs]), and Mishaps, if one exists. Table 2 contains the definitions of CASREPs and Mishaps. For CASREPs it is a summary of the longer definition contained within the cited publication, while for Mishaps it is the full definition.

**Table 2 – Definitions of Casualty Report (CASREP) and Mishap’s**

| CASREP | The primary means to communicate from a naval ship, shore activity or overseas base that the asset has incurred a casualty that is affecting its mission (i.e. degraded or out-of-service equipment). The rule of reporting mission impacts due to equipment failure is suspended during a maintenance availability unless the failed equipment will not be repaired during the availability. There are some |

13
exceptions such as the availability is less than 60 days or the ship is in a surge status (Naval Warfare Publication, 1987).

**MISHAP**

The primary means to document an “unplanned event or a series of events, which interfere with or interrupt a process or procedure and may result in a fatality, injury, or occupational illness to personnel or damage to property. They occur as a result of failing to identify and reduce or eliminate hazards. Mishaps are classified according to the severity of resulting injury, occupational illness, or property damage. Property damage severity is generally expressed in terms of cost and is calculated as the sum of the costs associated with Department of Defense (DOD) property and non-DoD property that is damaged in a mishap. The mishap classification is used to determine the type of investigation, report, and record keeping required as a result of the mishap (“Navy & Marine Corps Mishap and Safety Investigation, Reporting, And Record Keeping Manual,” 2005).”

There are several authors (as cited in Belland et al., 2010; Gibb and Olson, 2008) who for aircraft mishap analysis use the Human Factors Analysis and Classification System (HFACS) risk assessment tool (Reason, 1990), but the literature research conducted did not find similar literature on CASREPs. Literature research also revealed there is no existing framework to accomplish the desired analysis of the predictive powers of cumulative DFSs.

The second hypothesis is related to the question – is there a way to control risk by predicting CASREPs and Mishaps as a DFS can be a risk indicator due to it being a variation from normal operation. If this is true, this will also further systems engineering efforts associated with resilience engineering (B. S. Blanchard and W. J. Fabrycky, 2006). Resilience engineering aims to manage risk in a proactive manner while acknowledging the inherent complexity of systems (Patriarca et al., 2018). A part of resilience engineering is the need for predictive indicators to “explicitly monitor risk, and to make appropriate tradeoffs between required safety levels and production and
economic pressures (Madni and Jackson, 2009).” There are several articles that discuss the need for well-defined predictor indicators, also known as leading indicators, and reporting systems (Lofquist, 2010; Remawi et al., 2011; Skogdalen et al., 2011; U.S. Navy Safety Center, 2018) which will allow for proactive well-informed decisions to be made before objectionable consequences occur (Lofquist, 2010). Predictive indicators will also increase the knowledge, K, of the risk analysts which will then decrease the amount of uncertainty, Q, in the risk (R) equation $R = (Q, K, C)$ where C is a consequence (Aven and Ylönen, 2016).

“Uncertainty is considered the state, even partial, of deficiency of information related to, understanding or knowledge of, an event, its consequences or likelihood (ISO, 2009).” One area of uncertainty is the interaction of the deviations already known within a system specifically the cumulative effect of DFSs. This is supported by research by Dekker (2011) where he discusses five concepts ([1] scarcity and competition, [2] small steps, [3] sensitive dependence on initial conditions, [4] unruly technology, and [5] contribution of the protective structure) that may result in an organization unexpectedly drifting into failure. Three of these concepts are discussed further:

- Scarcity and competition; there is a constant challenge within the Government over the cost of projects and the inability to control costs (United States Government Accountability Office, 2014) and the commercial industry has many of the same issues.
- Small steps: examples of this include the relaxation of requirements such as documented in DFSs within DoD and the changing of maintenance periodicity as cited by Dekker and the

- Unruly technology (or in our case complex systems); as previously stated complex systems are unique as the interaction of how they work together is sometimes surprising to the developers when the system actually exceeds expectations such as an aircraft exceeding specification requirements. However, the interaction of the system when a small step has occurred (e.g., foam coming off of the external fuel tank, etc.) is not always understood or appreciated.

Årstad and Aven (2017) discuss the issue of complacency and how an organization can experience a major accident although they had no intention of pushing the edges of the safe operating zone. They also discuss the inability of an organization to recognize leading indicators of unsafe operations and this inability increases over time as the organization becomes complacent. This is another way of saying competent organizations can drift into failure without even realizing it. Failure is being defined here as a major accident or a casualty occurs. They go on to state this challenges normal practices and the references that backup the normal practice by asking what is safety-relevant and safety-critical and they emphasize the importance of the role of uncertainty in the prevention of major accidents (Årstad and Aven, 2017).

This work is not attempting to address every gap in the literature already cited but has selected four articles for in-depth analysis.

1. Nielsen (2006) - *Risk Management: Lessons from Six Continents*: “Risk management is essential to recognize and develop input to meet the different
needs for the project and respective stakeholders’ success throughout the seasons of a pipeline project’s life—a project’s spring season (from the identification of a possible need that may become a project to its financing/funding), a project’s summer season (project execution), a project’s fall season (project use), and a project’s winter season (sustainable recycling) (Nielsen, 2006).” The paper further developed the types of risks for eight categories of risk factors to be used throughout each season as previously discussed. However, there is no mention of DFSs during any of the discussion about seasons or risk factors.

2. Madni & Jackson (2009) – *Towards a Conceptual Framework for Resilience Engineering*: The authors believe safety is a dynamic characteristic which must take into account variations from normal operation. This will further cite the need for predictive indicators as previously discussed. However, the drift correction, discussed in the article, does not address DFSs.

3. Leveson (2011) – *Applying systems thinking to analyze and learn from events*: while this paper focused on learning from past events, it discusses some key aspects such as how safety must be controlled at the system level and not the component level as it is a system property and not a component property. Also, as previously discussed, during operations of a system, safety is achieved or maintained partly by the design of the system and partly by the effective control of the system during operations. And while she addresses how deviations may occur to a system, during production or operation, and the need for the operators to adjust their mental model of the system when this occurs, she does not discuss the need to evaluate departures from specifications that are known.
4. Morrow et al (2014) – *Exploring the relationship between safety culture and safety performance in U.S. nuclear power operations*: Recognized that in high-reliability industries, as accidents happen only in extremely rare occurrences, as previously discussed, more frequent lesser events can be an indicator of degrading system performance. Yet based on the survey used within the article, DFSs were not considered.
Chapter 3 - Methodology

3.1 Hazard and Risk Assessment

Hazard and Risk Assessment (HRA) is the use of available information in a systematic way to identify hazards and probabilities and to predict possible consequences. Skogdalen and Vinnem (2012) discuss how precursor incidents in the North Sea oil and gas industry “can be combined using available information from a precursor incident as input to Quantitative Risk Analysis - methodology to identify hazards, probabilities, safety barriers and possible consequences.” They go on to state that the “combined use of well-known data sets and traditional hazard analysis techniques can be a less struggling approach than introducing new techniques, and still ensure a more complete cause and risk picture in complex systems (Skogdalen and Vinnem, 2012).” Traditional statistical analysis techniques and known data sets are used in this research to accomplish the analysis.

3.2 Research Approach

In this section, the dataset and the approach flowchart are discussed. The results will be discussed in Chapter 4. The statistical tests selected are common so the methodology for the detailed calculations on how to accomplish the test will not be discussed. The approach flowchart to review the dataset and their interrelationships are captured in Figure 1, which is located after an explanation of the dataset.

3.2.1 Dataset

Although the granting of DFSs and the occurrence of casualties/incidents happen in many industries and Government organizations, U.S. Navy information for twelve (12)
similar hulls (hull is defined as a ship) that were delivered by the shipbuilder to the U.S. Navy during the period selected for analysis, which is from delivery of the hull until December 2016, are used. One exception to this time-period occurs with Hull 3’s period lasting only until May 2015 due to it entering an extended maintenance availability at that time. An explanation of each data type and the quality checks used are covered in the subsequent subsections to include if the twelve hulls met the criteria for being in-service (i.e., representative of hulls during the operational and support phase and no longer in the warranty period of the shipbuilder [see Section 3.2.1.4 for more detailed information]).

The use of actual U.S. Navy data adds credibility to the research that data obtained through simulation may not necessarily provide. Additionally, the U.S. Navy has recently had an increase in operational tempo, due to world conditions, which has resulted in an increase in the number of DFSs being written. A recent United States Government Accountability Office report found the number of “casualty reports—incidents of degraded or out-of-service equipment—have doubled over the past 5 years (United States Government Accountability Office, 2015).”

3.2.1.1 Departure from Specification (DFS)

For the U.S. Navy surface ships and submarines, COMUSFLTFORCOM (2015) subdivides DFSs into Permanent or Temporary and Major or Minor. A permanent DFS reflects a permanent change to the ship or submarine while a temporary DFS allows a condition to exist for a specific period until permanent repairs can be conducted. The period is variable and identified within the DFS. A major DFS is one that affects “(a) performance; (b) durability; (c) reliability or maintainability; (d) interchangeability; (e) effective use or operation; (f) weight or appearance (where a factor); (g) health or safety;
(h) system design parameters such as schematics, flow, pressures, or temperatures; or (i) compartment arrangements or assigned function (NAVSEA, 2015).” An example of a major DFS is High-Pressure Air Valve having an additional backup ring added to the seat to eliminate free play (Hull 6–0011–2012). A minor DFS is simply one that does not meet the definition of a major DFS. An example of a minor DFS is a deferral of hydrostatic testing of fittings (Hull 6–1077–2011).

The Naval Sea Logistics Center maintains the electronic DFS database repository which captures 100 data fields, for every DFS, not just whether one is a permanent/temporary or if one is a major/minor (see Appendix A for complete listing of the fields and Appendix B for a listing of the DFSs, by hull, used in this analysis). For the 12 hulls used as part of this research, an analysis was conducted on the quality of the data for the 9,573 DFSs associated with the 12 hulls specifically looking at (1) end date of temporary DFSs and (2) whether the DFS was Canceled when it should have been Archived.

(1) To ensure temporary DFSs were not counted more than once as some had multiple extensions (the most common was one extension [1,033 DFSs had this] with the worst having nine extensions [only 1 DFS had this]), all extensions were treated as a single DFS using the original start date and the end date (i.e., corrected date) of the last extension. (An extension is issued when the original ‘approved to date’ is unachievable.) This ensured the entirety of the temporary condition was only captured once which resulted in the deletion of all extensions, 1,763 DFSs.

(2) A review of the 1,041 canceled DFSs resulted in the finding that some DFSs were inadvertently canceled by someone as the temporary condition no longer
existed but as the condition did exist at one time, it should have been archived and not canceled. An example is after the installation and testing of the Automatic Identification System (AIS) on Hull 7, the DFS was canceled as it was no longer required (Hull 7-1041-2011). This last condition resulted in the conversion of 41 DFSs to Archived and only 1,000 DFSs were Canceled for various reasons such as inadvertently taking out a number or the use of a Ship’s Force DFS to track a shipyard issued DFS.

After the removal of extensions and canceled DFSs, the total number of DFSs for analysis went from 9,573 to 6,810 (Active and Archived), active meaning it was a temporary condition for that hull at the completion of the analysis period.

3.2.1.2 Casualty Report (CASREP)

For the U.S. Navy, there are four categories of CASREPs used. As Category one (CAT 1) is only used by the Naval Education Training Command, that category was not used in this analysis. Table 3 contains the definitions of the remaining three categories that were used in the analysis (Naval Warfare Publication, 1987).

<table>
<thead>
<tr>
<th>CASREP – Category Codes</th>
<th>EQUIPMENT CRITERIA</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Deficiency in mission essential-equipment which causes a minor degradation in a primary mission; or a major degradation and/or loss of a secondary mission.</td>
</tr>
<tr>
<td>3</td>
<td>Deficiency in mission essential equipment which causes a major degradation (but not loss) to a primary mission.</td>
</tr>
<tr>
<td>4</td>
<td>Total loss of a primary mission</td>
</tr>
</tbody>
</table>

The data contained within a CASREP message is captured in an electronic database. The data is subdivided into 16 categories which are then subdivided into 298 fields captured for each CASREP. The total number, for all three categories of
CASREPs, is 4,808 CASREPs for this analysis. As CASREPs are not canceled or extended, as DFSs are, the quality of the CASREP data was determined to be good and required no modification. It should also be noted when a CASREP is written there is a required statement to be added if a Mishap Report is required because of the CASREP. For the 4,808 CASREPs, there were none noted as needing a Mishap Report.

### 3.2.1.3 Mishap Reports

For the U.S. DoD, there are four classifications of Mishaps (USD(AT&L), 2011) and the U.S. Navy Safety Center issued an additional fifth type (H) (U.S. Navy Safety Center, 2014). Table 4 contains these definitions of the classifications.

<table>
<thead>
<tr>
<th>MISHAP CLASSIFICATIONS</th>
<th>DEFINITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>The resulting total cost of damages to Government and other property is $2 million or more, a DoD aircraft is destroyed, or an injury or occupational illness results in a fatality or permanent total disability.</td>
</tr>
<tr>
<td>B</td>
<td>The resulting total cost of damages to Government and other property is $500,000 or more, but less than $2 million. An injury or occupational illness results in permanent partial disability, or when three or more personnel are hospitalized for inpatient care (which, for mishap reporting purposes only, does not include just observation or diagnostic care) as a result of a single mishap.</td>
</tr>
<tr>
<td>C</td>
<td>The resulting total cost of property damages to Government and other property is $50,000 or more, but less than $500,000; or a nonfatal injury or illness that results in 1 or more days away from work, not including the day of the injury.</td>
</tr>
<tr>
<td>D</td>
<td>The resulting total cost of property damage is $20,000 or more, but less than $50,000; or a recordable injury or illness not otherwise classified as a Class A, B, or C mishap.</td>
</tr>
<tr>
<td>H</td>
<td>All other events not meeting the DoD thresholds (i.e., Hazards, Near Misses, and Mishaps that do not meet the Mishap Reporting Threshold.</td>
</tr>
</tbody>
</table>

The data contained within a Mishap Report is also captured in an electronic database managed by the U.S. Navy Safety Center. The data is subdivided into 16 fields that are captured for each Mishap Report. The initial total number, for all five categories
of Mishaps, was 183 Mishap Reports for the 12 hulls analyzed, with zero Class A mishaps. A review of each Mishap Report was conducted to first determine which ones were outside the timeframe of the analysis, which resulted in the removal of 88. The 95 were then further analyzed to determine which ones were direct results of personnel not following standard safety practices, which resulted in the removal of an additional 89. This left only six Mishap Reports remaining to be analyzed as possibly having been a result of the accumulation of DFSs.

### 3.2.1.4 Determination of In-Service

Using data from the U.S. Navy results in a potential anomaly that may be present in other industries and should be considered as it impacts the analysis of that system. The Navy has a period immediately following delivery where the hull is under warranty, and thus not truly considered in-service. This period is to allow for at-sea testing of the various subsystems to verify they are operating as designed. This warranty period is followed by a maintenance period where any deficiencies are corrected and systems are upgraded. This maintenance period is commonly referred to by the U.S. Navy as a Post Shakedown Availability (PSA). It is not until this maintenance period completes that the hull is considered truly in-service ready for deployment. Although both temporary and permanent DFSs are written during the warranty and maintenance period prior to the hull entering the in-service period, casualties are not always reported in this period which takes months and sometimes years to complete. This is a significant distinction because if one is trying to determine the accumulative effect of DFSs to CASREPs and CASREPs are not being written, then the analysis to determine the impact will be skewed.
The results of whether the twelve hulls met the criteria for in-service (i.e., representative of hulls during the operational and support phase and no longer in the warranty period of the shipbuilder) is discussed in Chapter 4. As this research is focused in on the operational and support phase, this is a key determination.
<table>
<thead>
<tr>
<th>Data Set</th>
<th>Method</th>
<th>Analysis</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S. Navy Data (2004–2016): (1) Departures from Spec (Major/M.), (2) Casualty Reports (CSREP/C), &amp; (3) Mishap Reports (MAR)</td>
<td>Qualitative</td>
<td>Time Series</td>
<td>2 Hulls fail to meet criteria</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Graphical Display</td>
<td>Upward trend</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Generate box plots and Graphical Display</td>
<td>Information in framework does not clearly follow either</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Strength and direction of correlation determined by Class and hull</td>
</tr>
<tr>
<td></td>
<td>Linear &amp; Poisson</td>
<td>Qualitative</td>
<td>None identified as being related to DFSs.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Qualitative</td>
<td>Regression equation determined by Hull</td>
</tr>
</tbody>
</table>

Figure 1 - Approach Flow Chart
3.2.2 Qualify, Method & Analysis

3.2.2.1 Test for Trends and Rates

It is always helpful to plot out the data first before any analysis is conducted since plots provide the most basic insights, from which other behaviors and relationships can be determined. Below is an example of the analyses that can be run on the data with the last two discussing an alert limit which will be discussed later:

- Trend analyses: An increasing trend in CASREPs is an alert indicator of equipment deterioration which if not corrected can lead to major failures. An increasing trend in DFSs is an alert indicator of uncontrolled departures from specifications. Decreasing rates of occurrence indicate improvement.

- Rate analysis: High rates of occurrence in comparison to past history or in comparison to other Hulls indicates control problems. Jumps in rates of occurrence indicate anomalies. Low rates of occurrence indicate better control.

- Comparative Analysis of Numbers of DFSs and CASREPs: A Comparative analysis across Hulls identifies relative performances across Hulls which can include rankings.

- Monitoring of Occurrence Rates of DFSs and CASREPs: Monitoring of occurrence rates identifies when the occurrence rate exceeds control limit alert bounds.

- Monitoring of Accumulating DFSs and CASREPs Rates: Accumulative monitoring indicates when accumulating DFSs exceeds an alert limit in terms of correspondence to a high CASREP rate.
3.2.2.2 Test for Normality/Poisson and Outliers

The probability distribution of monthly DFSs in relation to CASREPs and Mishaps provides information on the occurrence profile along with the distribution characteristics. Chapter 4 will discuss which method was used.

3.2.2.3 Correlation and Regression Analyses of monthly DFSs and CASREPs & Mishaps

To test the hypothesis that there is a relationship between the accumulation of various DFSs and the number of CASREPs and Mishaps, there is a need to determine whether there is a positive, negative or no correlation between DFSs and CASREPs and/or Mishaps. This section describes the systematic statistical methods that were used to determine whether a correlation exists, and if so its magnitude. Multiple correlation methods, to include nonparametric, were used as the data, by the hull, may allow the use of these various methods. Chapter 4 will discuss which method was used.

3.2.2.3.1 Pearson’s correlation

The Pearson product-moment correlation coefficient is the most widely used correlation approach. The coefficient measures the strength of the linear relationship between the two variables in question.

There are five assumptions that must be acknowledged before using this approach. These assumptions are (1) the variables in question should be measured on a continuous scale; (2) these continuous variables should be paired; (3) there needs to be a linear relationship between the variables; (4) there should be no significant outliers in the
data; and (5) there should be bivariate normality (Laerd Statistics, 2017). These assumptions are discussed further in Chapter 4 when the results are discussed.

The Pearson correlation for a sample is termed $r$ and is derived from the following formula:

$$ r = \frac{\sum_{i=1}^{n} ((x_i - \bar{x})(y_i - \bar{y}))}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 \sum_{i=1}^{n} (y_i - \bar{y})^2}} $$

### 3.2.2.3.2 Spearman’s correlation

The Spearman rank correlation coefficient is a nonparametric measure. The coefficient assesses the monotonic relationships between two variables. In fact Myers and Well (2003) defines the Spearman correlation as “the Pearson correlation between the ranked variables.”

There are three assumptions that must be acknowledged before using this method: (1) there are two variables in question that are measured on a continuous and/or ordinal scale; (2) these variables should be paired; and (3) there needs to be a monotonic relationship between the variables (Laerd Statistics, 2017). These assumptions are discussed further in Chapter 4 when the results are discussed.

The Spearman correlation for a sample is termed $r_s$ and is derived from the following formula:

$$ r_s = 1 - \frac{6 \sum_{i=1}^{n} D_i^2}{n(n^2-1)} $$

### 3.2.2.3.3 Kendall Tau’s correlation

Kendall's Tau-b ($\tau_b$) correlation coefficient is another nonparametric measure that measures the association between two variables.

There are three assumptions that must be acknowledged before using this approach. These assumptions are (1) the two variables are measured on at least an ordinal scale (i.e. there are (a) two continuous variables, (b) two ordinal variables, or (c)
one continuous and one ordinal variable); (2) these variables should be paired; and (3) there needs to be a monotonic relationship between the variables. (Laerd Statistics, 2017). These assumptions are discussed further in Chapter 4 when the results are discussed.

The Kendall Tau correlation is termed $\tau_b$ and is derived from the following formula: $\tau_b = (C-D)/\sqrt{[(C+D+T_X) \times (C+D+T_Y)]}$ where $C$ is the number of concordant pairs and $D$ is the number of discordant pairs, where the number of concordant and discordant pairs are based on all distinct pairs of observations, and $T_X$ is the number of cases with ties on variable $X$ only and $T_Y$ is the number of cases with ties on variable $Y$ only.

3.2.2.3.4 Poisson Regression Analysis

To test the second hypothesis, if there is a correlation, a regression analysis is required. As the data in its raw form is “count data,” it was determined that a Poisson regression analysis was most appropriate. Greene (2003) states Poisson regression analysis may be appropriate when the dependent variable is a count, such as the arrival of a telephone call at a call center. The arrival of one call must be independent of the arrival of another call such that the arrival of one call will not make another likely, but the probability of the calls is understood to be related to such things as the time of day. Similarly, in the case of this analysis, the generation of one CASREP or Mishap is independent of the others and would not preclude or encourage the generation of another being written.

There are five assumptions that must be acknowledged before using this approach. These assumptions are (1) the dependent variable consists of count data; (2) there is one or more independent variable(s) that is measured on a continuous, ordinal or
nominal/dichotomous scale; (3) there should be independent observations; (4) the
distribution of the dependent variable follows a Poisson distribution; and (5) the mean
and variance of the dependent variable are the same, which is a normal outcome of a
Poisson distribution (Laerd Statistics, 2017). These assumptions will be addressed in
Chapter 4 when the results are discussed.

The following formula is a generic Poisson regression model:

$$\mu = \beta_0 + \beta_1 x_1$$

Penn State University (n.d.) states in the online course material that the
Poisson regression dependent variable (Y) is an observed count that follows the Poisson
distribution. The Poisson distribution for a random variable Y has the following
probability mass function for a given value $Y = y$:

$$P(Y = y | \lambda) = \frac{(\lambda^y y! e^{-\lambda})}{y!}, \text{ for } y = 0, 1, 2, \ldots.$$  

The single parameter $\lambda$ is the mean rate of occurrence for the event being
measured. For the Poisson distribution, it is assumed that large counts (with respect to the
value of $\lambda$) are rare.

The rate $\lambda$ is determined by a set of $p-1$ predictors $X=(X_1, \ldots, X_{p-1})$. The
expression relating these quantities is

$$\lambda = \exp \{ X \beta \}.$$  

Thus, the fundamental Poisson regression model for observation $i$ is given by

$$P(Y_i = y_i | X_i, \beta) = e^{-\exp \{ X_i \beta \}} \exp \{ X_i \beta \} y_i!.$$  

That is, for a given set of predictors, the categorical outcome follows a
Poisson distribution with rate $\exp \{ X \beta \}$. For a sample of size $n$, the likelihood for a
Poisson regression is given by:
This yields the log-likelihood:

\[
(\beta) = \sum I = 1n(y_iX_i\beta) - \sum I = 1n\exp\{X_i\beta\} - \sum I = 1n\log(y_i!).
\]

### 3.2.2.3.5 Linear Regression Analysis

If the data is manipulated, as is common in data analysis fields to see if there are other relationships, a Linear regression analysis maybe appropriate.

There are seven assumptions that must be acknowledged before you can use this approach. These assumptions are (1) there is one dependent variable that is measured on a continuous scale; (2) there is one independent variable that is measured on a continuous scale; (3) there should be a linear relationship between the variables (dependent and independent); (4) there should be independence in the observations; (5) there should be no significant outliers in the data; (6) there is homoscedasticity of the variances; and (7) the estimates of the regression equation are approximately normally distributed (Laerd Statistics, 2017). These assumptions will be addressed in Chapter 4 when the results are discussed.

The following formula is a generic linear regression model.

\[
Y = \beta_0 + \beta_1X + \varepsilon
\]

Where:

- \(Y\) is the dependent variable,
- \(\beta_0\) is the intercept or constant,
- \(\beta_1\) is the slope parameter/coefficient,
- \(X\) is the independent variable, and
- \(\varepsilon\) represents the errors.
3.3 Development of the Discussion and Conclusion Research Approach

The number of data fields associated with DFSs, CASREPs and Mishaps is: DFSs (6810*100 fields) + CASREPs (4808*298) + Mishaps (6*16) = 2,113,880 fields.

The 100 fields pertaining to a DFS were reviewed and it was determined that Hull Number (Field # 21) would be the pivot field to which every other field would be tied in the data analysis. The initial analysis file looked as follows:

<table>
<thead>
<tr>
<th>DEPARTURE #</th>
<th>DFS DATE (i.e., approval date)</th>
<th>QA12A - R APPROVING DATE (i.e., clearance date if temporary)</th>
<th>DFS Type</th>
<th>Permanently Approved Major</th>
<th>Permanently Approved Minor</th>
<th>Temporarily Approved Major</th>
<th>Temporarily Approved Minor</th>
<th>Status of Departure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hull 7-0001-2010</td>
<td>9/9/2010</td>
<td>2/4/2011</td>
<td>Minor</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Archive</td>
</tr>
</tbody>
</table>

Figure 2 - Example DFS Analysis File

To evaluate the relationship between departures from specifications and subsequent casualties and mishaps it is required to understand which DFSs were active during a given month by removing the temporary DFSs that were cleared. To accomplish this, two different programs were required - the statistical analysis software program JMP and Microsoft Project (to capture those DFSs that were open and closed in the same month). Equations 1 and 2 contain how the number of active DFSs for each month was determined:

(1) \( N(k) = n(k) + N(k-1) - r(k) \)

\( N(k) = \) total number of DFS in month
\( k = \) total number of DFS existing at end of month \( k \)
\( n(k) = \) number of new DFS occurring in month \( k \)
\( N(k-1) = \) total number of DFS in month \( k-1 \)
\( r(k) = \) number of DFS removed in month \( k \)

(2) \( N(k)-N(k-1) = n(k) - r(k) = nn(k) \) where \( nn(k) = \) net number generated per month
As the data fields for DFSs, CASREPs, and Mishaps all have different definitions, it was determined the only element in common was time (i.e., when the event occurred or when the DFS was in effect). The analysis period chosen was by month to capture the fluctuation of DFSs that opened and closed following delivery. The start date of the analysis was at the delivery of the hull, the first of which (Hull 1) was in October 2004 and the last of which was in June 2015 (Hull 12). The end date of the analysis was chosen as December 2016.

Figure 3 depicts how the framework was developed that was used for analysis for each hull separately and how each row was then added together for the analysis of all hulls together (i.e., a class) with the constant being month and year. Starting in the top left corner of Figure 3 is a depiction of a completed DFS form. This information is used to populate 3.a of Figure 3. The information contained in 3.a is run through the two software programs previously discussed to populate 3.b of Figure 3. Scheduling information is also loaded into 3.b. The lower left-hand corner is a completed CASREP form. This information is used to populate 3.c of Figure 3 with Hull and CASREP number (i.e., 1-2014080), CASREP Category Code, and Date of CASREP. The information from 3.c is then used to populate 3.d of Figure 3 if there is a desire to determine the number in each category of CASREP, and 3.b. The lower right-hand corner of Figure 3 is a depiction of a completed Mishap form. This information is used to populate 3.e of Figure 3 with Event Date & Time, Mishap Class, Hull Number, Equipment Identification Code and Event Narrative. The information from 3.e is then used to populate 3.f of Figure 3 if there is a desire to determine the number in each Class of Mishap, and 3.b.
There is a recognition that there are potential additional outside factors that influence whether a CASREP or Mishap is generated. These include suspect material (i.e., sub-vendor material potentially not meeting specifications) not already identified by a DFS (e.g., under-wall thickness of pipe fittings, etc.), Preventive Maintenance System (PMS) not being accomplished on a component as required and not already identified by a DFS, operator error due to training issues or fatigue, operational tempo (i.e., pushing the ship and crew beyond normal limits), inattention to surroundings which causes an injury, and the political ramifications of having a CASREP or Mishap written (i.e., the crew is less inclined to identify an issue if it will reflect poorly on the ship’s crew). These other factors are shown below in Figure 4 and were not included in this research with the
exception being the “injury” factor captured by a Mishap, as previously discussed. Although there is an overlap between the CASREP and Mishap circles it was not intended to show that both are needed to be reported as this analysis determined there were no instances in which both were written for the same occurrence.

Figure 4 - CASREP and Mishap Factors
Chapter 4 - Results

The results of the methodology just presented will be discussed in the various Sections within this Chapter. The purpose of this lead in paragraph is to present Figure 5, which is a graph of the data for each hull, which shows the number of DFSs, CASREPs, and Mishaps for each hull although Mishaps were so infrequent as to not be visible on the scale of the graph, but occurred on Hulls 1, 2, 5 and 6. These reflect the actual numbers of each category prior to using the JMP software and Microsoft Project to populate the framework. All remaining results reflect the use of the framework.

![Figure 5 - Data Broken Down by Hull](image)

4.1 Test for In-Service

Using the framework developed and explained in Chapter 3, a quantitative analysis was accomplished on all hulls to determine if they should be considered in-service. All hulls passed with exception of Hulls 10 and 11. Due to warranty issues, Hull 10 had an extremely long PSA, 28 months which resulted in it being in a maintenance availability for over 65% of this analysis period. This resulted in only 7 months post-PSA time or
less than 17% as of the date of this analysis period concluding, Dec 2016. For Hull 11, as of the date of this analysis period concluding, Dec 2016, it was still within its PSA and thus never entered in-service.

4.2 Test for Trends

The plot of the total number of DFSs along with the two components (Major and Minor) that make up the total is plotted against the number of CASREPs and Mishaps for Hulls 1 – 9 plus 12 treated as a class is shown in Figure 6.

![Figure 6 -- Plot of Monthly DFSs and CASREPs & Mishaps for Hulls 1 – 9 + 12](Note: there are two different Y-axis scales in use)

It is also useful to plot Casualty Rates Versus Month After Initiate Date. Figures 7 – 9 below show those results for all 12 hulls that were in the original analysis before Hulls 10 and 11 were removed.
Figure 7 - Hulls 1 - 4

Figure 8 - Hulls 5 - 8
Figures 10 - 19 below shows the collection of the individual hull plots of the number of Major DFSs and the cumulative number of CASREPs versus a common time scale for the individual hulls. Major DFSs were selected as they, by definition, have the largest potential impact. The x-axis reflects the number of months since the starting point of the analysis, the left y-axis reflects the number of Major DFSs current within that month, and the right y-axis reflects the cumulative number of CASREPs. As one can see there is an upward trend in Major DFSs over the analysis period. These all indicate increasing rate of CASREPs with nearly a constant rate of DFSs.
Figure 10: Hull 1 Major DFSs (left y-axis) and the cumulative number of CASREPs (right y-axis) vs time.
Figure 11 - Hull 2 Major DFSs (left y-axis) and the cumulative number of CASREPs (right y-axis) vs time
Figure 12. Hull 3 Major DFSs (left y-axis) and the cumulative number of CASREPs (right y-axis) vs time.
Figure 13 - Hull 4 Major DFSS (left y-axis) and the cumulative number of CASREPs (right y-axis) vs time

$Y = 0.6172X + 13.34$

$R^2 = 0.8307$

$Y = 0.027X^2 + 1.017X + 113.22$

$R^2 = 0.99$
Figure 14: Hull 5 Major DFSs (left y-axis) and the cumulative number of CASREPs (right y-axis) vs time

$\gamma = -0.0027x^2 + 1.265x - 55.5$

$R^2 = 0.9812$

$\gamma = 0.0241x^2 + 2.5528x - 173.72$

$R^2 = 0.9878$
Figure 15 - Hull 6 Major DFSSs (left y-axis) and the cumulative number of CASREPs (right y-axis) vs time
Figure 16 - Hull 7 Major DFSS (left y-axis) and the cumulative number of CASREPs (right y-axis) vs time
Figure 17 - Hull 8 Major DFSs (left y-axis) and the cumulative number of CASREPs (right y-axis) vs time
Figure 18: Hull 9 Major DFSs (left y-axis) and the cumulative number of CASREPs (right y-axis) vs time

- Hull 9 # of Major DFS:
  \[ y = -0.0054x^2 + 1.6111x - 102.12 \]
  \[ R^2 = 0.8849 \]

- Hull 9 Cum CASREPs:
  \[ y = 0.0533x^2 - 8.8196x + 361.88 \]
  \[ R^2 = 0.995 \]
Figure 19 - Hull 12 Major DFSs (left y-axis) and the cumulative number of CASREPs (right y-axis) vs time.

- **Linear Hull 12 # of Major DFSs**: $y = 1.747x - 227.08$, $R^2 = 0.9187$
- **Poly. Hull 12 Cum CASREPs**: $y = 0.0966x^2 - 24.923x + 1611.7$, $R^2 = 0.9391$
4.3 Tests for Normality/Poisson, Outliers, Correlation and Regression Analysis

Although there are multiple correlation methods, to include parametric and nonparametric, the Spearman Rank correlation method was used as the data did not follow a normal distribution, according to the Shapiro-Wilk test for normality, so the most widely used correlation approach of Pearson’s Product Moment Correlation (Laerd Statistics, 2017), was determined to be inappropriate. The Spearman’s rank-order correlation analyses assumptions discussed in Section 3.2.2.3.2 were met as the framework produced paired continuous variables which have a monotonic relationship. This also validated the assumptions for Kendall Tau discussed in Section 3.2.2.3.3.

The Poisson Regression analyses assumptions discussed in Section 3.2.2.3.4 were met as the framework produced (1) a dependent variable that consisted of count data; (2) there is one independent variable that is measured on a continuous, ordinal or nominal/dichotomous scale; (3) there are independent observations; (4) the distribution of the dependent variable follows a Poisson distribution as verified by graphical analysis; and (5) the mean and variance of the dependent variable are the same, which is a normal outcome of a Poisson distribution. Outliers were identified and determined it would be appropriate to include them in the analysis.

The Linear Regression analyses assumptions discussed in Section 3.2.2.3.5 were met as (1) there is one dependent variable that is measured on a continuous scale; (2) there is one independent variable that is measured on a continuous scale; (3) there is a linear relationship between the variables (dependent and independent); (4) there is independence in the observations; (5) there are no significant outliers in the data; (6) there is homoscedasticity of the variances; and (7) the estimates of the regression
equation are approximately normally distributed once the cumulative number of CASREPs was determined.

To determine if there is a relationship between the accumulation of various DFSs and the number of Casualties and Mishaps, the hulls were grouped together (i.e., a class) and then each hull was analyzed separately. The analysis was conducted with each DFS category, Major or Minor, and combined (Major plus Minor) as the independent variable for the hull and total number of CASREPs as the dependent variable. For the ten remaining hulls, 1-9 and 12, the total number of CASREPS (CATs 2, 3 and 4), is 4,585. There are six Mishaps qualitatively addressed separately under the discussion associated with each hull as when these were quantitively analyzed the results were not statistically significant. The regression analyses were conducted in a similar manner with each DFS category as the independent variable and each CASREP as the dependent variable although they were only accomplished at the hull level. Although the correlation results listed reflect Spearman’s rank-order, in several instances the Kendall Tau had a larger association when CAT 2 CASREPs were broken out from the combination of CASREPs although this resulted in non-statistically significant results for CAT 3 CASREPs given the small number of them for each hull when they were present in the data.

4.3.1 Class Analysis (Hulls 1-9 and 12 only)

Hulls 1-9 and 12 had one CAT 4 CASREP and 1.7% CAT 3 CASREPs. The total number of CASREPS (CATs 2, 3 and 4) were then analyzed for each DFS category and the total number of DFSs. There was a positive correlation between Total # of Major and Minor DFSs and Total # of CASREPs, \( r_s(145) = 0.89, p < 0.0005 \), a positive correlation between Total # of Major DFSs and Total # of CASREPs, \( r_s(145) = 0.89, p < 0.0005 \), and
a positive correlation between Total # of Minor DFSs and Total # of CASREPs, \( r_s(145) = .899, p < 0.0005 \).

### 4.3.2 Hull 1

Hull 1 had zero CAT 4 CASREPs and 1.8% were CAT 3 CASREPs. The total number of CASREPs (CATs 2 and 3) were then analyzed for each DFS category and the total number of DFSs. There was a positive correlation between Total # of Major and Minor DFSs and Total # of CASREPs, \( r_s(145) = .343, p < 0.0005 \), a positive correlation between Total # of Major DFSs and Total # of CASREPs, \( r_s(145) = .239, p = 0.004 \), and a positive correlation between Total # of Minor DFSs and Total # of CASREPs, \( r_s(145) = .348, p < 0.0005 \).

There were two Mishaps: one Class D - Sonar Unit Power Processing Unit - Light smoke in sonar processing unit; occurred during a maintenance period, and one Class H - Galley deep sink heaters - Acrid odor/light smoke from deep sink heaters; these occurred during a maintenance period. A qualitative review of DFSs resulted in none being identified as a precursor to these Mishaps.

A Poisson regression analysis was run. The regression equations are:
Total # of CASREPs = 1.0530497 + 0.0022306 x (Total # of Major and Minor DFSs), a statistically significant result, \( p < 0.0001 \).

Total # of CASREPs = 0.8912472 + 0.009601 x (Total # of Major DFSs), a statistically significant result, \( p < 0.0001 \).

Total # of CASREPs = 1.1452841 + 0.0026857 x (Total # of Minor DFSs), a statistically significant result, \( p < 0.0001 \).
Using the results of the regression analysis, the following relationship is determined on how DFSs can predict future Casualties.

A linear regression analysis was performed on the cumulative number of CASREPs and Major DFSs. The regression equation is:

\[ \text{CASREPS1} = -86.357 + 5.219 \times (\text{Total # of Major DFSs}) \]

a statistically significant result, \( p < 0.0001 \).

Using the results of the linear regression analysis, the following relationship is determined on how DFSs can predict future Casualties.
Figure 21 shows that with 95% confidence that once you reach ~78 Major DFSs that for every new Major DFS you should expect to have 5 additional CASREPs.

4.3.3 Hull 2

Hull 2 had zero CAT 4 CASREPs and 1% were CAT 3 CASREPs. The total number of CASREPS (CATs 2 and 3) were then analyzed for each DFS category and the total number of DFSs. There was a positive correlation between Total # of Major and Minor DFSs and Total # of CASREPs, $r_s(125) = .291$, $p = 0.001$, a positive correlation between Total # of Major DFSs and Total # of CASREPs, $r_s(125) = .250$, $p = 0.005$, and a positive correlation between Total # of Minor DFSs and Total # of CASREPs, $r_s(125) = .280$, $p = 0.001$.

There was one Mishap Class B which captured the towed array parting from the tow cable due to an unknown material failure. A qualitative review of DFSs resulted in none being identified as a precursor to this Mishap.
A Poisson regression analysis was run. The regression equations are:

Total # of CASREPs = 1.041544 + 0.0012963 x (Total # of Major and Minor DFSs), a statistically significant result, \( p < 0.0001 \).

Total # of CASREPs = 1.0197571 + 0.00448 x (Total # of Major DFSs), a statistically significant result, \( p < 0.0001 \).

Total # of CASREPs = 1.0576135 + 0.0017821 x (Total # of Minor DFSs), a statistically significant result, \( p < 0.0001 \).

Using the results of the regression analysis, the following relationship is determined on how DFSs can predict future Casualties.

![Figure 22 - Hull 2 Associated Departures Occurring Versus CASREPS (Existing Background CASREPS Removed)](image)

A linear regression analysis was performed on the cumulative number of CASREPs and Major DFSs. The regression equation is:

\[ \text{CASREPS1} = -43.6873938204202 + 3.54623921417916 \times (\text{Total # of Major DFSs}), \] a statistically significant result, \( p < 0.0001 \).

Using the results of the linear regression analysis, the following relationship is determined on how DFSs can predict future Casualties.
Figure 23 - Hull 2 Linear Regression of CumCASREPs by Major DFS (MDFS)

Figure 23 shows that with 95% confidence that once you reach ~45 Major DFSs that for every new Major DFS you should expect to have 4 additional CASREPs.

4.3.4 Hull 3

Hull 3 had zero CAT 4 CASREPs and less than 1% of CAT 3 CASREPs. The total number of CASREPS (CATs 2 and 3) were then analyzed for each DFS category and the total number of DFSs. There was a positive correlation between Total # of Major and Minor DFSs and Total # of CASREPs, $r_s(101) = .231$, $p = 0.019$, a positive correlation between Total # of Major DFSs and Total # of CASREPs, $r_s(101) = .184$, $p = 0.062$, and a positive correlation between Total # of Minor DFSs and Total # of CASREPs, $r_s(101) = .243$, $p = 0.013$.

There were no Mishaps.

A Poisson regression analysis was run. The regression equations are:
Total # of CASREPs = 1.6845662 + 0.00004624 x (Total # of Major and Minor DFSs), a statistically significant result, p < 0.2544.

Total # of CASREPs = 1.6536423 + 0.0025223 x (Total # of Major DFSs), a statistically significant result, p = 0.2469.

Total # of CASREPs = 1.6920922 + 0.0005598 x (Total # of Minor DFSs), a statistically significant result, p < 0.2589.

A linear regression analysis was performed on the cumulative number of CASREPs and Major DFSs. The regression equation is:

\[ \text{CASREPS} = -93.5978635621738 + 5.29605811895948 \times (\text{Total # of Major DFSs}) \]

a statistically significant result, p < 0.0001.

Using the results of the linear regression analysis, the following relationship is determined on how DFSs can predict future Casualties.
Figure 25 shows that with 95% confidence that once you reach ~43 Major DFSs that for every new Major DFS you should expect to have 5 additional CASREPs.

4.3.5 Hull 4

Hull 4 had the only CAT 4 CASREP for this analysis and less than 3% were CAT 3 CASREPs. The total number of CASREPS (CATs 2, 3 and 4) were then analyzed for each DFS category and the total number of DFSs. There was a positive correlation between Total # of Major and Minor DFSs and Total # of CASREPs, $r_s(105) = .432$, $p < 0.0005$, a positive correlation between Total # of Major DFSs and Total # of CASREPs, $r_s(105) = .441$, $p < 0.0005$, and a positive correlation between Total # of Minor DFSs and Total # of CASREPs, $r_s(105) = .420$, $p < 0.0005$.

There were no Mishaps.

A Poisson regression analysis was run. The regression equations are:
Total # of CASREPs = 1.1383937 + 0.0038808 x (Total # of Major and Minor DFSs), a statistically significant result, p < 0.0001.

Total # of CASREPs = 0.4355005 + 0.0266083 x (Total # of Major DFSs), a statistically significant result, p < 0.0001.

Total # of CASREPs = 1.2790088 + 0.0043302 x (Total # of Minor DFSs), a statistically significant result, p < 0.0001.

Using the results of the regression analysis, the following relationship is determined on how DFSs can predict future Casualties.

A linear regression analysis was performed on the cumulative number of CASREPs and Major DFSs. The regression equation is:

CASREPS1 = -114.941170285154 + 8.1409033197736 x (Total # of Major DFSs), a statistically significant result, p < 0.0001.

Using the results of the linear regression analysis, the following relationship is determined on how DFSs can predict future Casualties.
Figure 27 shows that with 95% confidence that once you reach ~38 Major DFSs that for every new Major DFS you should expect to have 8 additional CASREPs.

4.3.6 Hull 5

Hull 5 had zero CAT 4 CASREPs and 2% were CAT 3 CASREPs. The total number of CASREPS (CATs 2 and 3) were then analyzed for each DFS category and the total number of DFSs. There was a positive correlation between Total # of Major and Minor DFSs and Total # of CASREPs, $r_s(99) = .285$, $p = 0.004$, a positive correlation between Total # of Major DFSs and Total # of CASREPs, $r_s(99) = .233$, $p = 0.019$, and a positive correlation between Total # of Minor DFSs and Total # of CASREPs, $r_s(99) = .291$, $p = 0.003$.

There was one Mishap a Class D where a specific component overheated which caused a minor fire. A qualitative review of DFSs resulted in none being identified as a precursor to this Mishap.
A Poisson regression analysis was run. The regression equations are:

Total # of CASREPs = 1.639336 + 0.0016278 x (Total # of Major and Minor DFSs), a statistically significant result, p = 0.0002.

Total # of CASREPs = 1.592188 + 0.0070939 x (Total # of Major DFSs), a statistically significant result, p < 0.0001.

Total # of CASREPs = 1.656042 + 0.0020878 x (Total # of Minor DFSs), a statistically significant result, p = 0.0003.

Using the results of the regression analysis, the following relationship is determined on how DFSs can predict future Casualties.

![Figure 28 - Hull 5 Associated Departures Ocurring Versus CASREPS (Existing Background CASREPS Removed)一直都图.png](attachment:Figure%2028%20-%20Hull%205%20Associated%20Departures%20Ocurring%20Versus%20CASREPS%20(Existing%20Background%20CASREPS%20Removed).png)

A linear regression analysis was performed on the cumulative number of CASREPs and Major DFSs. The regression equation is:

\[
\text{CASREPS}_1 = -46.7258828784051 + 9.27255302643598 \times \text{(Total # of Major DFSs)},
\]

a statistically significant result, p < 0.0001.

Using the results of the linear regression analysis, the following relationship is determined on how DFSs can predict future Casualties.
Figure 29 shows that with 95% confidence that once you reach ~19 Major DFSs that for every new Major DFS you should expect to have 9 additional CASREPs.

**4.3.7 Hull 6**

Hull 6 had zero CAT 4 CASREPs and 1.5% were CAT 3 CASREPs. The total number of CASREPS (CATs 2 and 3) were then analyzed for each DFS category and the total number of DFSs. There was a positive correlation between Total # of Major and Minor DFSs and Total # of CASREPs, $r_s(83) = .497$, $p < 0.0005$, a positive correlation between Total # of Major DFSs and Total # of CASREPs, $r_s(83) = .441$, $p < 0.0005$, and a positive correlation between Total # of Minor DFSs and Total # of CASREPs, $r_s(83) = .495$, $p < 0.0005$.

There were two Class C Mishaps one being associated with an Emergency Diesel Generator and the other associated with the Towed Array. A qualitative review of DFSs resulted in none being identified as a precursor to these Mishaps.
A Poisson regression analysis was run. The regression equations are:

- Total # of CASREPs = 0.9561829 + 0.0049026 x (Total # of Major and Minor DFSs), a statistically significant result, \( p < 0.0001 \).
- Total # of CASREPs = 0.8576902 + 0.021355 x (Total # of Major DFSs), a statistically significant result, \( p < 0.0001 \).
- Total # of CASREPs = 1.0096218 + 0.006161 x (Total # of Minor DFSs), a statistically significant result, \( p < 0.0001 \).

Using the results of the regression analysis, the following relationship is determined on how DFSs can predict future Casualties.

![Figure 30 - Hull 6 Associated Departures Occurring Versus CASREPs (Existing Background CASREPS Removed)](image)

A linear regression analysis was performed on the cumulative number of CASREPs and Major DFSs. The regression equation is:

\[ \text{CASREPS}_1 = -57.545 + 6.824 \times \text{(Total # of Major DFSs)}, \text{a statistically significant result, } p < 0.0001. \]

Using the results of the linear regression analysis, the following relationship is determined on how DFSs can predict future Casualties.
Figure 31 shows that with 95% confidence that once you reach 30 Major DFSs that for every new Major DFS you should expect to have 7 additional CASREPs.

### 4.3.8 Hull 7

Hull 7 had zero CAT 4 CASREPs and 1.4% were CAT 3 CASREPs. The total number of CASREPS (CATs 2 and 3) were then analyzed for each DFS category and the total number of DFSs. There was a positive correlation between Total # of Major and Minor DFSs and Total # of CASREPs, \( r_s(76) = .261, p = 0.021 \), a positive correlation between Total # of Major DFSs and Total # of CASREPs, \( r_s(76) = .185, p = 0.105 \), and a positive correlation between Total # of Minor DFSs and Total # of CASREPs, \( r_s(76) = .270, p = 0.017 \).

There were no Mishaps.

A Poisson regression analysis was run. The regression equations are:
Total # of CASREPs = 1.0391262 + 0.00245 x (Total # of Major and Minor DFSs), a statistically significant result, \( p = 0.0098 \).

Total # of CASREPs = 0.9605777 + 0.0143877 x (Total # of Major DFSs), a statistically significant result, \( p = 0.0041 \).

Total # of CASREPs = 1.065129 + 0.0028295 x (Total # of Minor DFSs), a statistically significant result, \( p = 0.0137 \).

Using the results of the regression analysis, the following relationship is determined on how DFSs can predict future Casualties.

A linear regression analysis was performed on the cumulative number of CASREPs and Major DFSs. The regression equation is:

\[
\text{CASREPS1} = -11.5573491928633 + 6.66079014443501 \times (\text{Total # of Major DFSs}), \text{ a statistically significant result, } p < 0.0001.
\]

Using the results of the linear regression analysis, the following relationship is determined on how DFSs can predict future Casualties.
Figure 33 shows that with 95% confidence that once you reach 13 Major DFSs that for every new Major DFS you should expect to have 7 additional CASREPs.

4.3.9 Hull 8

Hull 8 had zero CAT 4 CASREPs and 2.3% were CAT 3 CASREPs. The total number of CASREPS (CATs 2 and 3) were then analyzed for each DFS category and the total number of DFSs. There was a positive correlation between Total # of Major and Minor DFSs and Total # of CASREPs, $r_s(63) = .427$, $p < 0.0005$, a positive correlation between Total # of Major DFSs and Total # of CASREPs, $r_s(63) = .494$, $p < 0.0005$, and a positive correlation between Total # of Minor DFSs and Total # of CASREPs, $r_s(63) = .408$, $p < 0.0005$.

There were no Mishaps.

A Poisson regression analysis was run. The regression equations are:
Total # of CASREPs = 0.9776804 + 0.0073024 x (Total # of Major and Minor DFSs), a statistically significant result, p < 0.0001.

Total # of CASREPs = 0.8150531 + 0.0618326 x (Total # of Major DFSs), a statistically significant result, p < 0.0001.

Total # of CASREPs = 1.0120592 + 0.0081498 x (Total # of Minor DFSs), a statistically significant result, p < 0.0001.

Using the results of the regression analysis, the following relationship is determined on how DFSs can predict future Casualties.

A linear regression analysis was performed on the cumulative number of CASREPs and Major DFSs. The regression equation is:

\[ \text{CASREPS1} = -79.6111083174091 + 16.4695262999095 \times (\text{Total # of Major DFSs}), \text{ a statistically significant result, p < 0.0001.} \]

Using the results of the linear regression analysis, the following relationship is determined on how DFSs can predict future Casualties.
Figure 35 Hull 8 Linear Regression of CumCASREPs by Major DFS (MDFS)

Figure 35 shows that with 95% confidence that once you reach 15 Major DFSs that for every new Major DFS you should expect to have 16 additional CASREPs.

4.3.10 Hull 9

Hull 9 had zero CAT 4 CASREPs and 1.0% were CAT 3 CASREPs. The total number of CASREPS (CATs 2 and 3) were then analyzed for each DFS category and the total number of DFSs. There was a positive correlation between Total # of Major and Minor DFSs and Total # of CASREPs, $r_s(54) = .594$, $p < 0.0005$, a positive correlation between Total # of Major DFSs and Total # of CASREPs, $r_s(54) = .548$, $p < 0.0005$, and a positive correlation between Total # of Minor DFSs and Total # of CASREPs, $r_s(54) = .561$, $p < 0.0005$.

There were no Mishaps.

A Poisson regression analysis was run. The regression equations are:
Total # of CASREPs = 0.432415 + 0.0083254 x (Total # of Major and Minor DFSs), a statistically significant result, p < 0.0001.

Total # of CASREPs = 0.3197991 + 0.0803744 x (Total # of Major DFSs), a statistically significant result, p < 0.0001.

Total # of CASREPs = 0.4604226 + 0.0091289 x (Total # of Minor DFSs), a statistically significant result, p < 0.0001.

Using the results of the regression analysis, the following relationship is determined on how DFSs can predict future Casualties.

A linear regression analysis was performed on the cumulative number of CASREPs and Major DFSs. The regression equation is:

CASREPS1 = -28.7668610575151 + 9.65245951395061 x (Total # of Major DFSs), a statistically significant result, p < 0.0001.

Using the results of the linear regression analysis, the following relationship is determined on how DFSs can predict future Casualties.
Figure 37 shows that with 95% confidence that once you reach 10 Major DFSs that for every new Major DFS you should expect to have ~10 additional CASREPs.

### 4.3.11 Hull 12

Hull 12 had zero CAT 3 & 4 CASREPs. The total number of CASREPs were then analyzed for each DFS category and the total number of DFSs. There was a positive correlation between Total # of Major and Minor DFSs and Total # of CASREPs, \( r_s(17) = .406, p < 0.0005 \), a positive correlation between Total # of Major DFSs and Total # of CASREPs, \( r_s(17) = .400, p < 0.0005 \), and a positive correlation between Total # of Minor DFSs and Total # of CASREPs, \( r_s(17) = .422, p < 0.0005 \).

There were no Mishaps.

A Poisson regression analysis was run. The regression equations are:

Total # of CASREPs = \(-0.381155 + 0.0135862 \times \text{(Total # of Major and Minor DFSs)}\), a statistically significant result, \( p < 0.0001 \).
Total # of CASREPs = -0.288461 + 0.0615349 x (Total # of Major DFSs), a statistically significant result, p = 0.0007.

Total # of CASREPs = -0.391347 + 0.017159 x (Total # of Minor DFSs), a statistically significant result, p < 0.0001.

Using the results of the regression analysis, the following relationship is determined on how DFSs can predict future Casualties.

![Figure 38 - Hull 12 Associated Departures Occurring Versus CASREPS (Existing Background CASREPS Removed)](image)

A linear regression analysis was performed on the cumulative number of CASREPs and Major DFSs. The regression equation is:

CASREPS1 = 2.50472091085809 + 0.829977783948903 x (Total # of Major DFSs), a statistically significant result, p < 0.0001.

Using the results of the linear regression analysis, the following relationship is determined on how DFSs can predict future Casualties.
Figure 39 shows that with 95% confidence that once you reach 10 Major DFSs that for every new Major DFS you should expect to have ~1 additional CASREPs.
Chapter 5 – Discussion and Conclusion

5.1 Discussion

The results indicate there is an impact on casualties occurring based on DFSs being approved although this is not true with respect to mishaps based on the data analyzed. This confirms the problem statement – Departures from Specifications (DFSs) are not being adequately addressed with respect to risk as they are reviewed in isolation from previously approved DFSs which can have disastrous consequences. And, while the results are helpful in many ways for the U.S. Navy, it is the systematic framework that will allow for standard statistical tests to evaluate the relationship between departures from specifications and subsequent casualties and mishaps for many Systems Engineering organizations or industry.

5.1.1 Scope of Analysis

First and foremost, it is important to ensure the quality of the data and to determine the scope of what is being analyzed. For the U.S. Navy data, it was important that the data reflected the proper categories of Archived, Active, and Canceled. The system-specific analysis represented the greatest challenges associated with using U.S. Navy data as it was determined there is an inconsistent use of system descriptions which did not allow this analysis from occurring. The DFS and CASREP forms were heavily reviewed to determine which were appropriate for the analysis. This analysis, more than any of the others, drives home the importance of being able to tie the DFS, CASREP and Mishap Reports together, via a common field, to allow feedback so future Mishaps and/or casualties can be averted. Labib and Read (2013) discussed in their
paper how organizations are not naturally programmed to learn so the fact there is no feedback mechanism today is not surprising. The U.S. Navy has an Equipment Identification Code for its components; however, even when it is listed as a required field on the form it is seldom filled out by the operator. This drives home the important point of creating various forms to be less free-form and contain more drop-down menus.

In addition, it was important to determine what was considered in-service. The results were surprising as the fact that Hull 12 is considered in-service while Hulls 10 and 11 are not is an indication of what can be a problem if you do not check. The fact that the framework allowed for this determination is an important outcome.

5.1.2 Framework

To accomplish the analysis, it was important to determine the number of active DFSs. Using the equations (1) and (2), the active number of DFSs by month was determined. Other time frames such as by quarter or week may be used by others once they determine what is appropriate for their analysis. Using the U.S. Navy data, it was determined the trend is increasing for the class of 10 hulls as well as for each of the individual hulls. Appendix C contains the JMP software code/script used in this analysis.

5.1.3 Correlation

The results for casualties, using Cohen (1988) standard categories, are as follows: (1) as a class (Hulls 1-9 & 12) there is a strong correlation for combined Major and Minor DFSs, Major DFSs separately and Minor DFSs separately and (2) a small to moderate correlation for 90% of the hulls (with hull 9 having a strong result).
Also of note, of the 33 correlation results, 27 are significant at the 0.01 level, 4 being significant at the 0.05 level and the remaining 2 results not meeting the statistically significant criteria. The highest non-0.05 p-value is associated with Hull 7 and Major DFSs where the p-value is 0.105 or 89.5% confident the null hypothesis can be rejected instead of the standard 95%. Then with the confidence listed in Table 5, based on the results for this dataset, the null hypothesis (H₀ – there is no relationship between cumulative Departures from Specifications [Waivers] and Casualties) can be rejected and the research hypotheses can be adopted.

### Table 5 - Hypothesis H1a Results

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Confidence Results</th>
<th>Ha Confirmed</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1a(1): There is a relationship between Combined Major and Minor DFSs and Combined Casualties.</td>
<td>98%</td>
<td>Yes</td>
</tr>
<tr>
<td>H1a(2): There is a relationship between Major DFSs and Combined Casualties.</td>
<td>90%</td>
<td>Yes</td>
</tr>
<tr>
<td>H1a(3): There is a relationship between Minor DFSs and Combined Casualties.</td>
<td>98%</td>
<td>Yes</td>
</tr>
</tbody>
</table>

The good news for the U.S. Navy is the issuance of DFSs are not causing mishaps to occur, based on the data analyzed, so the null hypothesis cannot be rejected. And so, the research hypothesis - there is a relationship between cum Departure from Specifications and Combined Mishaps (Class A, B, C, D, and H) is not accepted.

However, this may be a unique case given the data utilized in this research. This should not infer that DFSs can be approved with no concern for mishaps occurring. Other data may reflect a different outcome.
5.1.4 Regression

The regression analysis for casualties is very promising. Of the 30 results, 27 are significant at the 0.01 level. Then with the confidence listed in Table 6, based on the results for this dataset, the null hypothesis ($H_0$ – The accumulation of DFSs is not a predictor of future Casualties) can be rejected and the research hypotheses can be adopted.

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Confidence Results</th>
<th>Ha Confirmed</th>
</tr>
</thead>
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<td>H2a(1): The accumulation of Combined Major and Minor DFSs is a predictor of future Casualties.</td>
<td>90%</td>
<td>Yes</td>
</tr>
<tr>
<td>H2a(1): The accumulation of Major DFSs is a predictor of future Casualties.</td>
<td>90%</td>
<td>Yes</td>
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<tr>
<td>H2a(1): The accumulation of Minor DFSs is a predictor of future Casualties.</td>
<td>98%</td>
<td>Yes</td>
</tr>
</tbody>
</table>

For mishaps, as there was no correlation, there is no prediction of future mishaps. And so, the research hypothesis - the accumulation of DFSs is a predictor of future Mishaps is not accepted.

5.2 Conclusion

As part of Strategic Planning and Change Management, specifically under lifecycle engineering, the objective of this research was to explore the relationship between accumulated departures from specifications and associated casualties and/or mishaps. This was accomplished in a systematic way by developing a framework. Although actual U.S. Navy data (DFSs, CASREPs & Mishaps) for the Operations and Support Phase were
used in this research, the framework can be used by non-U.S. Navy systems engineering organizations.

The impact of accumulated departures was analyzed and it was determined that there is a correlation between these accumulated departures and casualties and that they can be used as a precursor. The correlation between the number of occurring CASREPs and the accumulated number of existing DFSs was determined at the class level and for each individual hull with most of the resulting correlations to be statistically significant at the 0.01 level. The regression analysis between the number of occurring CASREPs and the accumulated number of existing DFSs was determined for the individual hull with most of the resulting correlations to be statistically significant at the 0.01 level.

Although this was not the case with mishaps, the analysis of both casualties and mishaps has increased the risk knowledge level available to the risk analyst, for the U.S. Navy data, and subsequently decreased their uncertainty. For it is important to remember during operations of a system, safety is achieved or maintained partly by the design of the system and partly by the effective control of the system during operations (Leveson, 2011) to include effective management of DFSs which is not possible without an effective framework.

5.3 Contributions

While the following is feedback on U.S. Navy Data, this may be applicable to other operating and engineering organizations.

- While mishaps are generally written, as the writing of them is enforced by an outside agency, the Navy Safety Center, a review of the data has determined CASREPs are not written in each instance based on a qualitative analysis of the
dataset. There are several reasons why this may be the case to include (1) too many CASREPs being written could be viewed as a negative reflection on the crew, (2) if repair parts are onboard the equipment is repaired and not reported through the CASREP system, and (3) there is no forcing function to write a CASREP.

- DFSs also are not consistently written from hull to hull for the same condition. These impact the ability to learn from the failure of the equipment from one hull to another. In addition, there is inconsistent use on what is captured by a DFS as some are global in nature such as material issues that affect multiple systems are captured on one DFS and other DFSs are part specific. One should be able to call up any system and get a listing of all DFSs (e.g., Archived, Active and even maybe Canceled).

The framework can be used as a tool to systematically store and catalog data, will be of use by others so they can run a similar analysis to show the impact that DFSs have on casualties which is the main contribution to the Engineering Management field. This also supports the current “resilience engineering” emphasis with the end result of using the framework is a better-informed Engineering Management organization!

5.4 Future Directions

There are three main areas being proposed for future directions: (1) system level analysis, (2) risk assessment, and (3) application tools and software.
5.4.1 System Level Analysis

The framework, with minor changes, can be used as a tool to support system level analysis and Figure 40 depicts a subset of the framework that could be used for this analysis. The following is an example of a system level approach:

Like the original framework depicted in Figure 3, the analysis starts with the forms and the information (i.e., Hull-Departure/CASREP/Mishap Number, [Start] Date, Clearance Date, Status and System [nomenclature] & Comments) is compiled. The compiled results are incorporated into the framework that lists the Date, Year, Month, DFS Number (and the months it is active), the Total Cumulative Number of Active DFSs for the system under analysis (e.g., Radar is depicted), and the Total Number of System related CASREPs.

To populate the framework depicted in Figure 40, a system is selected for analysis at the class level. An approach is by looking at the top 5 drivers of casualties by looking at
only the last three years of data and then over the entire analysis period to determine the most frequent failed part(s) as documented by the Associated Part Listing (APL) recorded on the CASREP. The primary system for the APL, along with their ranking, is listed in Table 7.

<table>
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<tr>
<th>System</th>
<th>Top 5 Last 3 years</th>
<th>Ranking for entire Analysis Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sonar</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Ship Control</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Radar</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Vent</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>High Pressure Air System</td>
<td>5</td>
<td>20</td>
</tr>
</tbody>
</table>

The secondary systems were also determined for each failed part. The secondary systems are those whose interaction in some way may have influenced the casualty in the primary system from occurring. Here is a listing of the secondary systems for each of the 5 systems listed in Table 7:

- **Sonar**: fiber optic, electrical (to include outboard cabling), ventilation (to include Air Conditioning (AC) plant), structure, and cooling water.
- **Ship Control**: Main Propulsion, High-Pressure Air Compressor (HPAC), Low-Pressure Air Compressor (LPAC), Secondary Propulsion, electrical & fiber optic cabling, ballast management system, interior communication, and primary interfacing systems being primary propulsion, ventilation, radar, and sonar.
- **Radar**: like sonar, this system has fiber optic, electrical (to include outboard cabling), ventilation (to include AC plant), structure, and cooling water.
- **Vent**: piping, electrical, structure and ship control.
- **High-Pressure Air System**: piping, air banks, electrical, structure, propulsion and ship control.
Note: To more accurately reflect a system’s approach for failure analysis based on how these systems are designed, a double failure approach was utilized. A double failure is defined as needing two failures (e.g., if the system had a battery backup then the loss of the primary electrical system failing would not be a cause of the casualty.)

As there are currently no consistent system markings of DFSs or CASREPs, the existing fields of each DFS and CASREP were used to determine which DFSs and CASREPs were associated with each of the five systems on a system basis. Thus, the qualitative analysis was conducted five times. A qualitative analysis was accomplished to determine when a DFS influenced a casualty to occur which was subsequently captured in a CASREP. This information was then added to the simplified version of the framework which was possible given the relatively small number of DFSs (the highest number of DFSs per system was 16). A portion of the simplified framework is depicted on the far right of Figure 40. The analyst would then accomplish statistical tests, as already discussed within this document, to determine if there is a correlation and based on those results if there is an ability to predict future casualties.

5.4.2 Risk Assessment

The framework used in this analysis should be expanded to include an analysis of risk (i.e., Risk Assessment) once it is a part of the approval process for each DFS. To ensure uniformity, it is recommended the assignment of the risk by the DFS approver be accomplished using a Wizard/Model-Driven tool to ensure consistency among the approvers for future analysis. Once the DFS is loaded into the framework than by using a Bayesian analysis, there can be an assessment of the accumulative risk of all DFSs (Vesely, 2017). In fact, it had been one of the research goals to accomplish this but the
dataset did not contain the documentation of the individual risk assessments for each DFS.

5.4.3 Application Tools and Software

The framework can also be automated to load the data as it becomes available. The software can also be developed to carry out the analyses automatically with the results being produced and updated on a periodic basis. Depending upon the analyst’s or the decision maker’s level of risk tolerance, different thresholds, and alert levels can be defined to identify the significant results. Tables, charts, and reports can be produced to allow for a better understanding of the data as usability is a key feature of the output.

Appendix D contains further insight into the framework along with some potential additional uses of it for optimizing operations and minimizing risk.
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## Appendix A – Departure from Specification Fields in Naval Sea Logistics Center (NAVSEALOGCEN) Database Repository

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Appendix B – Listing of DFSs, CASREPs and Mishaps

(this information is available from the author.)
Appendix C – JMP Script

// From an open data table that has a Start and End
// ask for the beginning date (for example 02/01/2006)
// ask for the ending date (for example 08/01/2016)
Names Default To Here( 1 );
//month.list={"Jan","Feb","Mar","Apr","May","Jun","Jul","Aug","Sep","Oct","Nov","Dec"};
dt.current = Current Data Table();
new window("Enter Date Range",<<modal,
    Panel box("Note",Text Box("This script operates on the current data table at run-time. The current data table is "||char(dt.current<<get name)||"")),
    Panel Box("Date Range",lineup box(ncol(3),spacing(15),Text box(""),Text Box("Month"),Text Box("Year"),Text Box("Beginning Date"),s.month=combo box(month.list),s.year=number edit box(),
    Text Box("Ending Date"),e.month=combo box(month.list),e.year=number edit box()
    //))
    Panel Box("Date Range", line up box(ncol(2), spacing(15), Text Box("Beginning Date"), s.date=number edit box(0),
        Text Box("Ending Date"), e.date=number edit box(0)
    ),
    s.date<< Set Format( Format( "ddMoNyyyy", 12 ) ),
    e.date<< Set Format( Format( "ddMoNyyyy", 12 ) ),
    s.date << set( Date MDY( 2, 1, 2004 ) ),
    e.date  << set( Date MDY( 1, 31, 2017 ) )
)
);
starting.date = s.date << get;
ending.date = e.date << get;
num.months = Date Difference( starting.date, ending.date, "Month", "actual" ) + 1;
dt = New Table( "Active Projects by Months" );
dt << New Column( "Date", Numeric, "Ordinal", Format( "ddMoNyyyy", 12 ) );
dt << New Column( "Number of Active Projects on Date", "numeric" );
dt << add rows( num.months )
For( i = 1, i <= num.months, i++,
    active.col = J( 1, N Row( dt.current ), 0 );
    date.ind = Date Increment( starting.date, "Month", i - 1, "actual" );
    Column( dt, 1 )[i] = date.ind;
    For( j = 1, j <= N Row( dt.current ), j++,
        active.col[j] = (Column( dt.current, "Finish" )[j] >= date.ind | Is Missing( Column( dt.current, "Finish" )[j] )) &
            Column( dt.current, "Start" )[j] <= date.ind
)
Column( dt, 2 )[i] = Sum( active.col );

dt<<new script("Overlay Plot",
Overlay Plot(
   X( :Date ),
   Y( :Number of Active Projects on Date ),
   Separate Axes( 1 ),
   Connect Points( 1 )
);
);
Appendix D – Improvements for Optimizing Operations and Minimizing Risks

Part I – an example of how to consolidate the individual reports (DFS is used below)

<table>
<thead>
<tr>
<th>DEPARTURE #</th>
<th>DFS Approval Date</th>
<th>Clearance Date (for temporary DFSs)</th>
<th>DFS Type</th>
<th>Permanent</th>
<th>Temporary</th>
<th>Status of Departure</th>
</tr>
</thead>
</table>

Part II – an example of how to consolidate the individual report types into specific information is shown below. Changes to this are easy such as the time frame may be changed if the date is important by just adding an additional column.

The following are the data requirements of future DFSs, CASREPs, and Mishaps which should be part of the input to further achieve the framework’s objective:

- Originator
- Highest level Component affected (e.g., ship, aircraft, etc.)
- Date (Year, Month and Day) and Time of Event
- Type of Document (e.g., DFS, Mishap Report, CASREP, etc.)
- Severity (e.g., Major, Minor, Class A, CAT 4, etc.)
- Additional Classification - if needed
- Clearance Date
- System/sub-system component affected - use of Standard (e.g., Expanded Ship Work Breakdown Structure [ESWBS]) System Menu Driven (Key)
- Equipment Identification Code - use of Standard (e.g., Expanded Ship Work Breakdown Structure [ESWBS]) System Menu Driven (Key)
- References - Use of Standard Library Menu
- Applicable Specifications - Use of Standard Library Menu
- Situation/Non-Compliance - Freeform
- Functions affected - Freeform
- Operational environment - (e.g., deployed, in the maintenance period, etc.)
- Comments/Recommendation - Freeform
- Date Answer Requested
- Submitting Activity - Login Auto-generated, user roles
- Risk Assessment - Wizard/Model-Driven
- Process-Work flow - Automated, Auto-archived, Transaction history
- Multi-Media - Embedded Multi-Media, Auto-archived
- If a CAS or Mishap the associated DFSs, if known at the time of entry
- Dates of Major events in (e.g., Maintenance Availabilities, Deployments, etc.)