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DEVELOPMENT AND SENSITIVITY ANALYSIS OF A MATHEMATICAL MODEL FOR MINE COUNTERMEASURE VESSELS IN THE EARLY DESIGN STAGE

by

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September 2020

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13. ABSTRACT (maximum 200 words)

With the evolving requirements of future mine countermeasure (MCM) operations, the operational capabilities of next-generation platforms must be sufficiently flexible to meet these changing needs. As the U.S. Navy’s current and leading platform solutions to address rising threats continually evolve, their operational capabilities are either directly derived from or influenced by the platforms’ architectural design parameters. Because of this mapping, traditional approaches of configuring operational systems around a vessel’s architectural design may have limited flexibility to accommodate design revisions and may make such revisions costly and time consuming.

Approaches centered around Model-Based Systems Engineering (MBSE) and digital engineering have seen success as simulation and modeling tools to better link architectural vessel designs to operational requirements of various types of vessels. To further extend on the MBSE approach to MCM operational requirements, this thesis considers steps necessary to establish a relationship between MCM capabilities and platform design parameters. This thesis explores potential related trade-offs by conducting a sensitivity study of the MCM vessel design parameters and their effects on the operational capabilities of the vessel. Such an approach can serve as the basis for a methodology influencing early-stage vessel design choices, as dictated by mission operational requirements.

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LIST OF ACRONYMS AND ABBREVIATIONS

α	cargo carriage multiplier
β	weight of power
Δ	vessel's displacement in long tons
Δ_{vol}	vessel's displacement in m^3
Δ_{cargo}	vessel's weight excluding propulsion system and fuel weight
Δ_{fuel}	weight of fuel
Δ_{prop}	weight of propulsion system
γ	proportion of all other weight not attributed to payload, propulsion system, or fuel
ρ	density of sea water
ASSET	Advanced Ship and Submarine Evaluation Tool
ASW	anti-submarine warfare
c	admiralty coefficient
CREATE	Computational Research and Engineering Acquisition Tools and Environments
DOD	Department of Defense
Fn	Froude number
Fn_v	volumetric Froude number
g	gravitational constant
HSSL	high-speed military sealift
HSV	high speed vessel
IDHE	Integrated Hydrodynamic Design Environment
INCOSE	International Council on Systems Engineering
L	length in m
LCS	Littoral Combat Ship
L/D Ratio	lift to drag ratio
LEAPS	Leading Edge Architecture for Prototyping Ships
LT	long ton

MBSE	Model-Based Systems Engineering
MCM	mine countermeasures
MCMV	mine countermeasures vessel
MIW	mine warfare
MOE	measures of effectiveness
MP	mission packages
NAVSEA	Naval Sea Systems Command
nm	nautical miles
NSWCCD	Naval Surface Warfare Center Carderock Division
OPV	offshore patrol vessel
P	payload
P_s	ship’s power
R	range in nm
SE	Systems Engineering
SFC	specific fuel consumption
SoS	system-of-systems
SPM	self-protective measures
SUW	anti-surface warfare
SWBS	Ship Work Breakdown Structure
U.S.	United States
USV	unmanned surface vehicle
UUV	unmanned underwater vehicle
UWIED	underwater improvised explosive devices
V	ship’s speed in m/s
V_k	ship’s speed in knots
WWI	World War I
WWII	World War II

EXECUTIVE SUMMARY

Using the Model-Based Systems Engineering (MBSE) approach, this thesis develops a simple model to link the design parameters of a vessel, specifically a mine countermeasures vessel (MCMV), to its operational performance. The model can serve as a tool to make a preliminary feasibility assessment of vessel design parameters and potentially avoid costly redesign or modifications later in the development life cycle. The following paragraphs highlight the sea mine threats and the importance of mine countermeasures (MCM) summarized in the thesis, as well as the methodology and model used. The following paragraphs also provide a synopsis of the result analysis and conclusions presented in the research.

A. SUMMARY OF MINE THREATS AND IMPORTANCE OF MCM

Sea mines have been widely employed with the purpose of reducing naval freedom of action. Improvements in technology over the years have reduced the costs and increased the ease of employing sea mines, making them the weapon of choice for adversaries of the United States (U.S.) Navy (Marolda 2015). Coupled with the emergence of underwater improvised explosive devices (UWIED), sea mines pose an increased threat to the U.S. Navy (Truver 2008). As such, it is important for the U.S. Navy to focus on and build its MCM capabilities to meet this rising threat. The current and leading MCM platform solution for the U.S. Navy is the Avenger-class (MCM 1) MCMV, but with it poised for decommissioning over the next few years, the Littoral Combat Ship (LCS) is slated to be the next generation MCM platform replacement. Yet, budget cuts and delivery delays within the LCS program due to vessel design issues have resulted in a huge setback for the MCMV (Eckstein 2017), and there are no firm plans for the LCS to address rising sea mine threats, nor is there any validation that the LCS is sufficient for such a purpose.

As is evident in the LCS program, complexity in vessel design often results in the need for costly and time-consuming modifications. This problem emphasizes the need for a tool enabling navies to conduct preliminary assessments related to changing requirements or design rework during the initial conceptualization phase of the system's life cycle.

Understanding how changing design parameters can lead to tradeoffs in operational performance in the early stages of the system's life cycle allows decision makers to choose the most effective and efficient design modifications, which will be less costly and detrimental as compared to changes made in the later stages. In the case of MCMVs, this understanding can be achieved through the development of a simple model linking vessel design parameters to key operational performance metrics such as speed, range, and payload carrying capacity.

B. METHODOLOGY AND MODEL USED

The use of MBSE as a simulation and modeling tool to better link architectural vessel designs to their combat system requirements has seen some success, as demonstrated by the extension and application of Dr. McKesson's five-parameter method (McKesson 2006) for offshore patrol vessels (OPV) (Pisani 2013) and high-speed vessels (HSV) (Tran 2014).

This thesis leverages this methodology and extends its application on MCMVs by first establishing a relationship between length, which is a more concrete and intuitive design parameter, and the vessels' displacement. By using the relationship of the volumetric Froude number (Fn_v) to the admiralty coefficient (c) for a database of MCMVs, this research develops a mathematical model using speed, range, payload, and displacement. Through the selection of vessel input parameters and variables, the model was capable of calculating a predicted displacement value, and a general relationship between the key operational performance parameters of the MCMV—speed (V), range (R), and payload carrying capacity (P)—could be established. Further sensitivity analysis was conducted to understand the extent of the effects on displacement values and variable relationships.

C. RESULTS ANALYSIS

The resultant displacement equation in terms of length, speed, range, and payload was obtained to establish the relationship between speed, range, and payload for a given displacement value through relationship plots, using the MATLAB program. For a displacement value of 3361LT, for example, as range/payload increases, speed decreases. As payload/speed increases, range decreases and as range/speed increases, the payload decreases. The obtained relationship shows that at least one of the parameters would need to be sacrificed to improve the other two variables. In addition, the results show the magnitude of range differences changes significantly with varying payloads. At a high payload of 900LT, the increasing speed results in a greater decrease in range, and at a low payload of 200LT, increasing speed results in a smaller decrease in range. These findings provide insights about the consequence on the range (which is a measurement of endurance out at sea) for specific payloads at varying speeds. It should be noted that the above numerical values are used simply to demonstrate the methodology and are not necessarily indicative of actual values or recommended range of parameters.

A discrepancy in the calculated displacements versus the actual literature displacement values was identified during the validation process of the model. The discrepancy was resolved through realistic adjustments of three other input variables in the overall displacement equation: (1) cargo carriage multiplier (α), (2) proportion of all other weight not attributed to the propulsion system, payload, or fuel (γ), and (3) specific fuel consumption (SFC). With the adjustments, the general relationships between V, R, and P were maintained, although the feasible payload range was significantly reduced, which was attributed to the increase in α and γ values, thereby decreasing the allowable payload weight possible.

Sensitivity analysis was also conducted to understand the effects of changing α, γ, and SFC, as well as the weight of power (β) values. These were input variables to the displacement equation and could be pre-determined values. Suitable and realistic intervals were selected and varied, and a sensitivity ratio was calculated. The results show that γ is the most sensitive variable, followed by α, SFC, and then β as the least sensitive. Further analysis was also conducted to understand the effects on the relationship between V, R, and P. Varying of α and γ had the greatest effect on P, while varying β had an effect on feasible V in the lower ranges. Varying SFC had insignificant effects on the operational parameters.

D. CONCLUSION AND RECOMMENDATIONS

The thesis concludes that the developed model provides preliminary insights pertinent to the MCMV operational parameters in determining feasible vessel design parameters such as length. In all, the results obtained show that the approach recommended in this thesis has the potential to link vessel design parameters to their operational performance through the construction of simple models to allow for effective representation of relationships in vessel design. This successful method could most certainly be expanded to other types of operational vessels.

The following recommendations emerge from the thesis findings. Firstly, the research approach centered on static MCM systems available on the vessel, so further research could focus on the analysis of unmanned underwater vehicles and/or unmanned surface vehicles, which are common MCM systems in many MCMVs today. Secondly, since there was a lack of readily available payload weight data on the MCM subsystems, the value could only be estimated. This value could be further refined to get a better estimate as the MCM systems to be incorporated become known. Lastly, there also was a lack of MCMV data points used to establish the relationship between length and displacement. A wider range of MCMV data points would significantly improve the robustness of the model by obtaining a better fit that describes the relationship.

References

Eckstein, Megan. 2017. “Littoral Combat Ship Program Vastly Different a Year into Major Organizational, Operational Overhaul.” USNI News. September 06. https://news.usni.org/2017/09/06/littoral-combat-ship-program-vastly-different-year-major-organizational-operational-overhaul.

Marolda, Edward J. 2015. “Mine Warfare.” Naval History and Heritage Command. April 09. https://www.history.navy.mil/research/library/online-reading-room/title-list-alphabetically/m/mine-warfare.html.

McKesson, Chris B. 2006. “A Parametric Method for Characterizing the Design Space of High Speed Cargo Ships.” *In Proceedings of the International Conference High Speed Craft – ACV’s, WIG’s & Hydrofoils*. http://resolver.tudelft.nl/uuid:51f7df49-c387-478b-97f3-5aa99aa40ff3.

Pisani, Christopher R. 2013. “Linking Combat Systems Capabilities and Ship Design through Modeling and Computer Simulation.” Master’s thesis, Naval Postgraduate School. https://calhoun.nps.edu/handle/10945/37695.

Tran, Hoang N. 2014. “A Preliminary Ship Design Model for Cargo Throughput Optimization.” Master’s thesis, Naval Postgraduate School. https://calhoun.nps.edu/handle/10945/42745.

Truver, Scott C. 2008. “Mines and Underwater IEDs in U.S. Ports and Waterways.” *Naval War College Review* 61, no. 1(Winter) 105–127. https://pdfs.semanticscholar.org/7b8f/ad1c3ea6973ea6f18b7a909f4c8cd703b317.pdf.

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I. INTRODUCTION

This chapter highlights the significance of sea mine threats to the United States (U.S.) Navy and how Mine Warfare (MIW) is still a relevant topic of concern for navies around the world. The chapter provides a summary of the types of sea mines currently in use and the growing threat of asymmetric MIW. As such, mine countermeasures (MCM) is an important capability that the U.S. Navy should aim to build and improve.

With the current and leading MCM solution for the U.S. Navy present in the form of MCM Vessels (MCMV), such as the Avenger-class (MCM 1) and Littoral Combat Ship (LCS 1), the focus of MCM capabilities should be on improving MCMV design to improve MCM operational performance. This chapter also discusses the different types of MCM missions and considers the key operational performance parameters as a measure of MCM effectiveness.

A. BACKGROUND

Since their inception in the 16th century, sea mines have been widely employed in naval combat, with the primary objective of reducing “naval freedom of action” (Morien 1999, 1). The technological evolution of sea mines has lowered the cost of producing and laying them and significantly increased the variety of its strategic employment. As such, MIW has become more complex, unpredictable, and more difficult to counter.

Sea mines have always posed a significant threat to U.S. naval operations. During the Korean War in the 1950s, the only four U.S. naval vessels lost in combat were sunk by adversary mines and accounted for 70 percent of all U.S. Navy casualties. In fact, the threat and effectiveness of sea mines were already evident during World War II (WWII), when sea mines had damaged or sunk four times more U.S. Navy ships than all other means of attacks combined (Marolda 2015). Hence, sea mines represent a highly favorable future weapon of choice for the U.S. Navy’s adversaries in naval combat. Figure 1 shows the number of U.S. Navy ships damaged or sunk by sea mines, in relation to other methods of attack, since post-WWII.

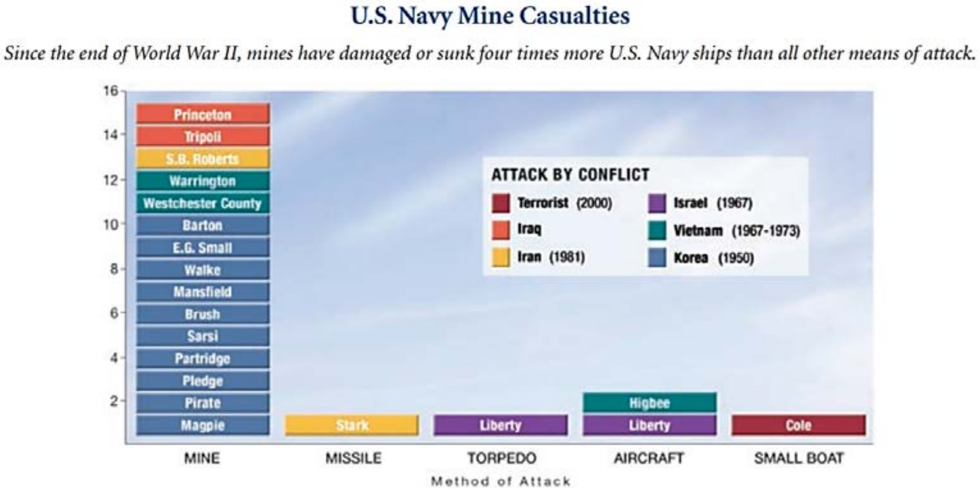

Figure 1. Number of U.S. Navy ships damaged/sunk by sea mines in relation to other methods of attack. Source: Program Executive Office Littoral and Mine Warfare (2009).

Sea mines can be classified based on three broad characteristics: their position in the water, their method of delivery, and their method of activation. Table 1 provides examples of the mines commonly used by various nations and how they are classified.

Table 1. Identification and classification of mines commonly used by various nations. Adapted from National Research Council (2002).

Country	Name	Position in Water	Method of Delivery	Method of Activation
Brazil	MCF-100	Moored	Aircraft laid Surface laid	Contact
Germany	SM G2	Bottom	Submarine laid	Influence
Iraq	Sigeel/400	Bottom	Aircraft laid Surface laid	-
Italy	Manta Mine	Bottom	Surface laid	Influence
Russia	SMDM Series	Bottom	Submarine laid	Influence

In addition to these commonly laid sea mines, the U.S. Navy faces threats from underwater improvised explosive devices (UWIED). These devices can act as inconspicuous sea mines, creating an asymmetric anti-access/area denial advantage for U.S. adversaries (Truver 2008). Not only can UWIEDs be controlled remotely, but they can discriminate targets for high accuracy and precision delivery, making them a significant force multiplier for an adversary. In addition, these devices and their resultant damage may not be attributable to any state, which further elevates the threat to the U.S. Navy.

B. MCM MISSIONS

To tackle such threats, MCM has always been an integral part of the U.S. naval strategy and improvements have been constantly made to this aspect. MCM missions can be categorized into two broad strategies: offensive or defensive. An offensive MCM mission aims to reduce the ability of adversaries in laying mine threats. This encompasses targeting adversary platforms and facilities involved in mine manufacturing and placement, ideally to destroy them before the mines are even laid. On the other hand, a defensive MCM mission focuses on actions after the mines have been laid by an adversary, and aims at reducing or eliminating the risks of mine threats to friendly forces (Joint Chiefs of Staff 2018). This thesis focuses on the defensive aspect of MCM missions and examines two approaches to defensive MCM: Passive and Active MCM missions.

1. Passive MCM

Passive MCM focuses on the aspect of limiting a ship’s ability to be sensed by a sea mine by reducing the electrical, acoustic, or magnetic signals emitted from the vessel, which can trigger a sea mine. This mission can be achieved by using onboard or external magnetic field reduction equipment, minimizing radiated noise, or reducing the pressure signature. The approach aims to reduce the risk to ships from sea mines without ships having to physically interact with the mines (National Research Council 2000).

2. Active MCM

Active MCM, on the other hand, involves interfering with the sea mine’s explosive functions or physically actuating/destroying it. This can be achieved through techniques known as minesweeping and mine hunting. Minesweeping can be conducted using platforms such as surface vessels or helicopters. A mechanical or influence sweep system towed by the platform can cut cables of moored mines, bringing them to the surface to be detonated thereafter by other means or via simultaneously influenced detonation. The technique requires variation in actuation methods, and its effectiveness is very much dependent on the sea mine’s characteristics (National Research Council 2000). Mine hunting employs aerial, surface, or subsurface sensors/sonars and neutralization systems to locate and dispose of sea mines. This technique, unlike minesweeping, is independent of the characteristics of the sea mines, and is generally a safer and more effective method of Active MCM (Joint Chiefs of Staff 2018).

C. MCM VESSELS

Since post-WWII, the U.S. Navy has developed and constructed 14 of the Avenger-class vessels with capabilities to detect, classify, and destroy sea mines. As a response to the evolving sea mine threat environment, the Littoral Combat Ship (LCS) was also developed in 2002 to accommodate interchangeable mission packages (MP). This includes an MCM MP capable of supporting MCM operations through the employment of an array of manned and unmanned assets to detect, localize, and neutralize surface, near surface, in-volume, and bottom mines (U.S. Navy 2016).

MCMVs such as the Avenger-class and the LCS constitute the leading MCM platforms for the U.S. Navy. As such, it is important to examine these vessels as platform solutions for the current and future MCM concept of operations and doctrine of the U.S. Navy in response to these rising threats.

1. Required Capabilities

Operational capabilities of the MCMV are directly derived from or influenced by the vessel’s architectural design parameters. With the ever-changing operational requirements inherent in future MCM operations, the operational capabilities of the next generation MCMVs must be sufficiently flexible to meet future MCM operational needs. The design of any MCMV must consider capabilities that allow it to perform its MCM task effectively and efficiently, while at the same time enhancing its survivability in a mine threat area. To achieve that, ship design must be considered together with the systems onboard.

a. Self-Protective Measures

As an integral part of MCMV design, self-protective measures (SPM) describe the measures that the vessel can undertake to enhance its survivability in a mine threat area. SPM may not serve as the long-term or definitive solution to a mine threat, but it is a necessary component for consideration when developing an MCMV. To accomplish its MCM operational requirements, the MCMV will be called upon to maneuver in a mine threat area, and the SPM serves to enhance its survivability in such a scenario (Sherman 1999). Some examples of SPM include the following:

- Influencing the acoustic, magnetic, pressure, or seismic signature of the vessel to lower the probability of mine actuation.

- Hardening of vessels through physical material enhancement to protect against mine actuation effects.

b. Reconnaissance and Neutralization Systems

Reconnaissance and neutralization capabilities for MCM describe operations such as search, detect, classification, and neutralization of mine threats. Early and sustainable reconnaissance capabilities in the MCMV are crucial to the vessel’s success in any MCM mission. A suite of effective reconnaissance systems can provide greater clarity of the insitu mine threats of a specific area, highlight the potential risks, and provide early warnings to forces for follow-on missions. A commander is then able to make a more informed and deliberate tactical decision with the added information.

The use of unmanned underwater vehicles (UUV) to augment MCMVs has become a common approach, as it reduces the exposure and risk to the crew when conducting MCM operations. In one recent study, the most critical UUV system attributes shown to result in capability improvements for support in MCM missions were UUV speed and UUV scan width (Camacho et al. 2017). With improvements to technology on these aspects, UUVs can be a significant force multiplier to future MCM operations. By providing a rapid and low vulnerability solution to mine threats, this aspect allows potential scalability to MCM operations, which enhances efficiency and effectiveness. The focus of this thesis, however, is on the performance of the MCMV itself, and hence, the discussion does not consider the performance of subsystems such as the UUVs.

2. Description of Existing Platforms

The Avenger-class (MCM 1) is the current MCM platform of choice for the U.S. Navy in conducting MCM operations. The Littoral Combat Ship (LCS), which has been developed as a replacement for the Avenger-class, is characterized by its flexibility to carry different mission packages suited for different mission needs.

a. Avenger-class (MCM 1) Vessel

The Avenger-class concept was developed in the 1980s, and it was designed to fulfill mine-sweeping/hunting capabilities on moored and bottom mines. A total of 14 Avenger-class MCMVs were commissioned from 1987 to 1994, and as of early 2019, there were 11 remaining operational Avenger-class MCMVs. Nevertheless, these MCMVs are due for decommissioning within the decade due to their aging systems (Axe 2019). Figure 2 shows a sketch of the Avenger-class MCMV.

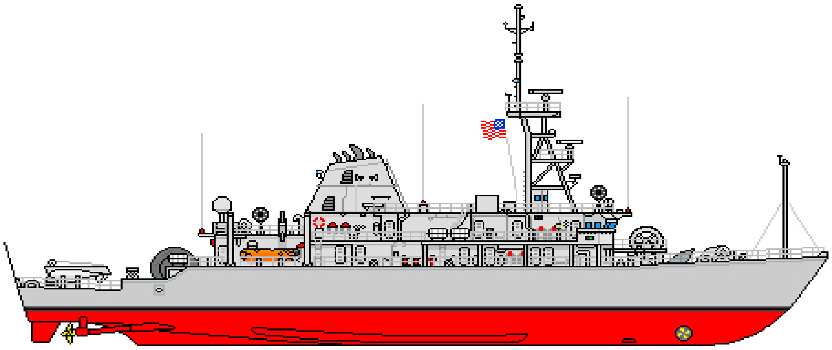

Figure 2. Sketch of the Avenger-class MCMV. Source: U.S. Navy (n.d.).

For the Avenger-class to effectively carry out its mission, it is equipped with MCM systems required for search, detect, and neutralization of sea mines. Table 2 shows the design specifications of the Avenger-class MCMV and its suite of MCM systems.

Table 2. Specifications for the Avenger-class MCMV design and performance parameters. Adapted from GlobalData Plc (n.d.).

Ship Design and Performance Parameters	
Length	68.82 m
Beam	11.89 m
Draught	4.6 m
Displacement	1,312 tons at full load
Speed	14 knots
MCM Systems	
AN/SQQ-32 Advanced mine hunting and classification sonar Raytheon search and detection sonar Thales Underwater Systems high-resolution sonar AN/SPS-73 surface search radar EX116 mod 0 ROV mine neutralization system AN/SLQ-48 ROV mine neutralization system	

b. Littoral Combat Ship

The LCS concept was developed in 2002 as a response to increasing asymmetric threats such as coastal mines, quiet diesel submarines, and terrorist boats in the littoral waters (GlobalData Plc n.d.). It encapsulates the idea of an operationally flexible ship that can be outfitted with interchangeable mission packages such as the MIW, anti-submarine warfare (ASW), and anti-surface warfare (SUW) packages to meet different mission requirements. Figure 3 shows an illustration of the LCS.

Figure 3. Illustration of the LCS. Source: Lockheed Martin (n.d.).

As of 2017, the LCS program has been reorganized to provide the U.S. Navy with eight operational LCS fitted with the MIW MP (Eckstein 2017). In addition to the basic suite of MCM systems, the MIW MP also consists of unmanned systems aimed to reduce exposure of sailors to such threats. Table 3 shows the design specifications of the LCS and the MIW MP.

Table 3. Specifications for the LCS design and performance parameters. Adapted from GlobalData Plc (n.d.).

Ship Design and Performance Parameters		
	Freedom Variant	Independence Variant
Length	118.1 m	128.5 m
Beam	17.6 m	31.6 m
Draught	4.3 m	4.6 m
Displacement	3,450 tons at full load	3,200 tons at full load
Speed	40+ knots	40+ knots
MCM MP		
AN/AQS-20A mine hunting sonar AN/ASQ-235 Airborne Mine Neutralization System Airborne Laser Mine Detection System AN/DVS-1 Coastal Battlefield Reconnaissance and Analysis Unmanned Influence Sweep System Knifefish unmanned underwater vehicle Barracuda mine neutralization system.		

D. CRITICAL MCM OPERATIONAL PERFORMANCE PARAMETERS

The success of an MCM operation can be evaluated using two key measures of effectiveness (MOE): average number of mines accurately detected and classified (MOE #1), and average time required to achieve mission success (MOE #2) (Lenzi 2020). Based on the results presented by Allison F. Lenzi in her thesis titled "Operational Analysis and Early-stage Design for Next Generation MCM Through Digital Engineering," the key design parameters of an MCMV that affect its ability to conduct defensive MCM (mine detection and classification) in the least amount of time are its speed and the performance specifications of its onboard MCM module/system (Lenzi 2020). In summary, the extent of the MOE's success could be characterized as being dependent on three critical operational performance parameters: (1) speed, (2) range, and (3) payload carrying capacity.

1. Speed

As highlighted by Lenzi, vessel speed was one of the most significant factors in influencing the effectiveness of both MOE #1 and MOE #2, and this factor remained consistent in different scenarios simulated. This was evident in the results presented, where the time to complete the mission (MOE # 2) was reduced by almost 50 percent when the vessel speed was greater than 12 knots as compared to when the vessel speed was less than 9 knots.

2. Range

Although the impact of the vessel range was omitted by Lenzi in her simulation model, the MCMV range is determined to be an important factor in ensuring MCM mission success in this thesis. It measures the endurance of an MCMV and affects the extent of its reach in relation to the mine threat position and geography. Range is also a factor that impacts the extent of coverage the MCMV has when out in sea performing its MCM critical mission.

3. Payload Carrying Capacity

Payload carrying capacity is defined here as the allowable weight of MCM systems that can be installed onboard the MCMV. As MCM systems differ, with each having its own capabilities reflected in the system's weight, there is a relationship between the payload carrying capacity and the MCM system performance of an MCMV. The variables that have the largest impact on the success of MOE #1 are minimum and maximum classification ranges of the system, detection delays in the system, probability of success of the systems, and the interactions between the mentioned variables (Lenzi 2020). As such, the payload carrying capacity, which determines what MCM system is feasible on board, is an important factor to consider when it comes to ensuring the success of an MCM operation.

E. LITERATURE REVIEW

This section provides a summary of the research conducted for this thesis. In particular, it highlights the literature that provided the motivation and background for exploring the use of Model-Based Systems Engineering (MBSE) methods as a simulation and modeling tool to better link vessel design specifically to MCM combat system requirements.

1. Importance of MCM for the U.S. Navy

Sydney J. Freedberg Jr. highlighted the U.S. Navy's lack of MCM capabilities back in 2015, with only 4.7 percent of the Navy's 275 warships dedicated to mine warfare. This number pales in comparison with the United States having to face naval mines from its near-peer competitors such as China and Russia, which have an estimated 100,000 and 250,000 naval mines inventory, respectively (Freedberg 2015). Since the end of WWII, sea mines have damaged or sunk four times more U.S. Navy ships than all other means of attacks combined, a statistic highlighted by Scott C. Truver in his study on the severity of threat that sea mines have had on the U.S. Navy. This threat has been on the rise with the proliferation of UWIEDs—cheap and inconspicuous mines that can be readily assembled from materials such as “fifty-five-gallon drums, other containers and even discarded refrigerators” (Truver 2012). Still, these UWIEDs can cause devastating effects; for example, repairs for *USS Samuel B. Roberts* came to $96 million, from “striking a Soviet-designed WWI-era contact mine” costing only an approximate $1,500 (Truver 2008).

The current fleet of MCMVs—the Avenger-class—will be due for decommissioning in the next decade, and its replacement vessel—the LCS, after facing issues with design reworks, delayed delivery, budget cuts, and reorganization—will number only eight such ships fitted with MCM MP (Eckstein 2017). This emphasizes the importance of having flexibility in ship design that can allow for changing requirements or design modifications in the initial conceptualization phase, which will be less costly and detrimental to the overall ship development life cycle.

2. Use of MBSE to Link Vessel Design to MCM Requirements

Christopher Pisani (2013) highlighted the alternative use of MBSE as a simulation and modeling tool to better link a vessel’s design to its combat system requirements. Such an approach can be successful, as demonstrated using Chris McKesson’s five-parameter method on Offshore Patrol Vessels (OPV) and selected mission profiles (Pisani 2013). Furthermore, there is potential in extending such an application to MCM mission requirements by leveraging the methodology used by McKesson (2006) and examining the effects on the MCMV through a sensitivity study. In his thesis for the Naval Postgraduate School, Hoang Tran (2014) already extended the application of the five-parameter method to High Speed Vessels (HSV), analyzing the combinations of speed, range, and payload to determine optimal rates of cargo delivery through displacement as a ship design parameter. Both approaches have demonstrated the possibilities of creating a model that can be used in influencing early-stage vessel design choices, as dictated by mission operational requirements.

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II. METHODOLOGY

A. MODEL-BASED SYSTEMS ENGINEERING

The traditional Systems Engineering (SE) processes used in the past are no longer effective in tackling modern systems. Over the years, systems have evolved to complex systems-of-systems (SoS) in order to meet the increasing social and technological needs of society today. As a result, system quality attributes, known as the “ilities” of the system, have become more challenging and demanding (Ramos, Ferreira, and Barcelo 2012). The “document-centric” approach of traditional SE processes lacks the ability to address these “ilities” sufficiently.

Hence, the MBSE initiative was introduced by the International Council on Systems Engineering (INCOSE), with the overall goal of improving quality/productivity and lowering risks throughout the development and life cycle of systems. As defined by INCOSE, MBSE is “the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases” (Hart 2015). The MBSE approach involves a shift from a “document-centric” to a “model-centric” one, where models can be interconnected in a shared data domain, using standard modeling syntax and languages. This provides the platform and mechanism to enable iterative verification and enhance traceability and impact analysis across the system’s life cycle.

B. APPLYING MBSE TO IMPROVE SHIP DESIGN

Henrique Gaspar et al. (2012) present the idea of a vessel as a “large, self-contained system with a large number of highly integrated systems and with many parts. All basic systems must be provided by the vessel itself within a very limited contained volume, and all changes to any system part tend to interact and influence other systems through complex relationships” (Gaspar et al. 2012, 5). Given the intricate relationship between the subsystems that exist within a ship, there are constraints and difficulties in configuring a vessel's architectural design through traditional approaches. Due to its limited flexibility in design reworks, it is often costly and time-consuming to do so.

In addition to ensuring that the vessel design meets the basic requirements of being sea-worthy, an increasing number of systems are being introduced to enhance a vessel's functionalities through improvements in technology. This is most apparent in the military context, where navy ships are built with a specific purpose—as a show of force and as a deterrence strategy. Given the dynamic operational and threat environment today, naval vessels need to be equipped with the systems that can adequately respond to challenges and threats, but at the same time, be sufficiently flexible to adapt and anticipate changing requirements. All these factors make ship design extremely complex.

In 2007, the Committee on Armed Services of the U.S. House of Representatives held a hearing on the *Acquisition Oversight of the U.S. Navy's Littoral Combat System.* As evident in the LCS program, having to conduct design reworks amid construction proved very costly and resulted in significant schedule delays. Lockheed Martin's first ship (LCS Freedom), which was initially estimated to cost $220 million, cost approximately $100 million more and delivery of the ship was significantly delayed. In his testimony before the committee, Rear Admiral Chuck Goddard, then program executive officer (PEO) for ships highlighted that there were "insufficient metrics and tools to seek trends early and inadequate oversight of design and construction by both the contractor and the Navy." At the same 2007 hearing, Vice Admiral Barry Paul E. Sullivan, then the Commander Naval Sea Systems Command, stated:

> A myriad of changes in hull structure, auxiliary systems and electronics take place and we were all caught, I would say, by the increasing complexity.

Approaches centered around MBSE and Digital Engineering have seen success as simulation and modeling tools for effectively linking the design of various types of vessels to their particular operational requirements. Through MBSE, an in-depth analysis of design change impacts to the vessel's systems and performance can be conducted in the early stages, and potentially prevent costly consequences later in the development life cycle.

C. EXISTING TOOLS FOR MODELING AND SYNTHESIZING

This section of the thesis briefly summarizes some of the current and traditional ship modeling and synthesizing tools used by naval architects. The Naval Sea Systems Command (NAVSEA) core mission of designing, building, delivering, and maintaining the Navy’s ships and systems capability through enhancing capability and improving reliability has driven them in adopting digital tools and technologies in ship design and analytic processes (NAVSEA n.d.). Its Carderock Division (NSWCCD) has created many of the early-stage ship design tools still in use today.

1. Advanced Ship and Submarine Evaluation Tool

The Advanced Ship and Submarine Evaluation Tool (ASSET) was built by the NSWCCD, which has maintained it for over 30 years. ASSET is primarily used in the earliest stages of ship design where various design disciplines such as hull structural design, resistance and propulsion, weight estimation, among others are combined. It utilizes the design spiral approach by which disciplines are analyzed one at a time, through multiple iterations, before reaching a balanced whole-ship model solution. The pitfall of ASSET is its inability to provide a higher level of design definitions required for in-depth analysis as design progresses, often resulting in loss of design integration. Consequently, the process of data recreation accounts for most of the time, cost, and error associated with the analysis (Kassel, Cooper, and Mackenna 2010).

2. Leading Edge Architecting for Prototyping Systems

The Leading Edge Architecture for Prototyping Ships (LEAPS) was also built by the NSWCCD and has been maintained by NSWCCD for over 20 years. LEAPS was developed as a solution capable of storing and performing detailed analyses obtained from various design tools and integrating them. The tool can mitigate the pitfalls of ASSET and is often used in conjunction with it. The LEAPS software serves to accelerate the modeling and design process by allowing for detailed analysis to be conducted with less effort (Kassel, Cooper, and Mackenna 2010).

3. Integrated Hydrodynamic Design Environment

The Integrated Hydrodynamic Design Environment (IDHE) was developed through the Computational Research and Engineering Acquisition Tools and Environments (CREATE), a Department of Defense (DOD) program, with the aim of providing a design tool with which a designer can easily interface. The IHDE tool has been in use and maintained over 20 years and has provided a “unified easy-to-use system” for designers to conduct analyses of ship hydrodynamics such as resistance, seakeeping, stability, and fluid-structure interactions (Kassel, Cooper, and Mackenna 2010).

The focus of this thesis, however, is not to highlight the pitfalls of such design tools and thus discourage their use, but to create a simple tool that can be used to construct a model based on the relationship between a vessel’s primary design parameters and their effects on the vessel’s operational performance. Beyond the vessel’s basic functionalities for “sea-worthiness,” this thesis specifically examines the effects on MCMV operational performance.

D. IDENTIFIED GAPS AND PROPOSED APPROACH

The gaps in the current vessel design approach, as evident in the LCS program, arise from the lack of metrics and tools available to quickly assess feasibility trends and tradeoffs early in the vessel development life cycle. These gaps have resulted in required design reworks amid construction, which has proven to be very costly.

As such, the proposed approach in this thesis is to construct a simple mathematical model by leveraging on the methodology of the five-parameter method created by McKesson. This method was initially developed as a (1) “very rapid tool for determining if a proposed design is worth pursuing further” (McKesson 2006) by providing insights to ship design feasibility and (2) allowing for exploration of the design space by conducting tradeoff analysis. In two published theses titled, “Linking Combat Systems Capabilities and Ship Design through Modeling and Computer Simulation” (Pisani 2013) and “A Preliminary Ship Design Model for Cargo Throughput Optimization” (Tran 2014), both authors successfully demonstrated the extension and application of the five-parameter method on OPVs and HSVs. This success has provided confidence that the method can also be extended to MCMVs, for which the operational requirements (discussed in Chapter I) would also be largely characterized by some the parameters modeled in the five-parameter method. Some other parameters that are more specific to MCM operational performance are also discussed in later chapters.

The question in hand would be whether the five-parameter method can be further extended to include effective trade-space analysis of vessel design specifically for the MCMV. As discussed previously, it is important for MCMV design to have flexibility that allows for changing requirements or design modifications in the initial conceptualization phase, when it is less costly and disruptive to the overall ship development life cycle.

1. Defining Common Terms Used

To better appreciate the working principles of the five-parameter method, included here is a list of common terms and their definitions that are key to understand the approach. The list is as follows:

- **L/D** Lift to Drag Ratio – The ratio of Lift, which is the upward force on the ship generated when it moves over water over Drag, which is the resistance that a vessel encounters in water, affecting the vessel's speed and fuel efficiency (Makiharju, et al. 2008).

- **Fn_v** Volumetric Froude Number – This is expressed as Fnvol = V/√[g(Δ_{vol})1/3] and represents a dimensionless quantity; it is used as a metric for speed in relation to a vessel's speed, length, and acceleration due to gravity (Pisani 2013).

- **g** Gravitational Constant – This constant represents the acceleration of gravity (known as the gravitational field strength) on the surface of the Earth at sea level measured to be at a value of 9.8 m/s^2 (Hall 2015).

- **SFC** Specific Fuel Consumption – This term refers to the overall fuel consumption of the machinery, on a specific or per-horsepower-hour basis. This data is collected from commercial sources such as engine catalogs (McKesson 2006).

- **Δ_{vol}** Displaced Volume is measured in cubic meters (m^3) – One m^3 of water = 0.9820056 tons of water. One ton of water = 1.018324 m^3 of water.

- **V_k** Vessel Speed is measured in knots – 1 nautical mile per hour = 1 knot. 1 m/s = 1.94384m/s.

2. Overview of McKesson's Five-Parameter Method

The McKesson five-parameter method was developed based on studies revealing that "it is possible to predict the characteristics that a ship will have from a very sparse set of early design requirements" (McKesson 2011). The method was not meant to replace existing tools for ship modeling and synthesis, such as ASSET or LEAPS, but to allow for a swift identification of ship design feasibility and facilitate the decision whether to continue pursuing a design. With the intent to enable "Very Simple Models" for initial top-level assessment, the parameters used in the method were deemed sufficient as predictors for ship design feasibility (McKesson 2011). Based on the findings by McKesson, Pisani, and Tran, some of the formulas and values are assumed and adopted for this thesis methodology.

a. Lift to Drag Ratio (L/D Ratio)

The L/D ratio is used in aerodynamics as a metric to determine the amount of lift (buoyancy for a vessel) with respect to the drag, and therefore, this ratio is useful in determining the amount of power required to move a vessel and its payload. Lift and drag are two opposing forces. A greater ratio represents a greater lift over drag, which means that there is less resistance experienced by the vessel, and conversely, a smaller ratio represents a greater drag over lift, and hence a higher resistance (Pisani 2013). A vessel design with a greater L/D ratio is therefore a more attractive one, as it represents greater efficiency in moving the ship.

b. Cargo Carriage Multiplier (α)

The weight of cargo carriage, in simple terms, refers to "the weight of the shopping bag into which the cargo is put" (McKesson 2010). This value differs with the design requirements and types of vessels (commercial versus military), as factors such as "protection" or "survivability" play a part in determining this value. Typical cargo/commercial vessels should have a lower weight of cargo value as compared to military vessels. The assumed value of 2 lbs/lb of cargo is used for military vessels such as the MCMV, which implies that for each pound of "cargo" to be carried, the weight of the carriage should generally be at least twice that (Pisani 2013).

c. Weight of Power (β)

The weight of power refers to the weight of the propulsion plant on the vessel, including propulsors and engines, but excluding the weight of the fuel. It can be inferred that a lower weight power would mean a more efficient vessel. Based on McKesson's analysis of an existing ship design, it is possible to determine the actual values for this metric as ranging from 8 to 10 lbs/hp. This author assumes the use of 10 lbs/hp for the calculation of the weight of power for an MCMV.

d. Specific Fuel Consumption (SFC)

The SFC measures how efficiently a vessel engine consumes fuel while operating. Typically, a lower SPC number would imply greater efficiency of the vessel. It is observed that the SFC value varies throughout vessel operation and strongly depends on the type of propulsion plant (Pisani 2013). Figure 4 shows the trend of SFC of selected propulsion gas turbine engines and their predicted trend in the future. McKesson deduced that engines in the future are likely to perform much better and become more efficient; hence, a downward trend would likely be observed. Based on the trend predicted by McKesson, an SFC of 0.33 lbs/hp-per hour is assumed here for MCMVs.

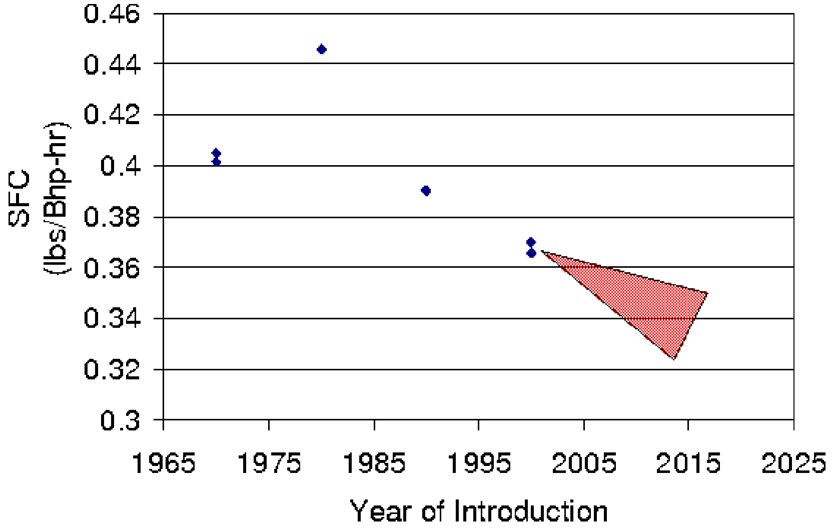

Figure 4. Propulsion gas turbine engines, SFC versus year of introduction, current and future engines. Source: McKesson (2006).

3. Goal of the Five-Parameter Method

A simple mathematical model was constructed by McKesson from two parameters: the L/D ratio and the volumetric Froude number (Fn_{vol}), which is described by the equation $Fn_{vol} = V_k / SQRT(g * \Delta_{vol}{}^{1/3})$. By plotting the L/D ratio for a collection of high-speed military sealift (HSSL) against their respective Fn_{vol} values, a "best practices curve" with the equation $L/D = 5 + 40\ (Fn_{vol})^{-3}$ was obtained as shown in Figure 5. The curve characterizes what McKesson calls a "frontier of the achievable" (McKesson 2006).

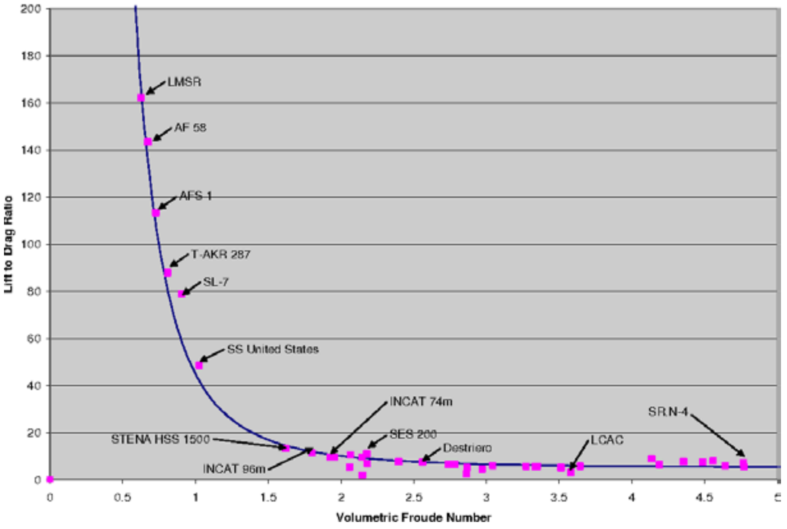

Figure 5. “Observed frontier” of McKesson’s best practices curve. Source: McKesson (2006).

Based on a desired Δ_{vol} and V_k value, a Fn_{vol} value can be obtained to derive a L/D ratio from the best practices curve. The L/D ratio parameter can be used as a tool to predict Drag. Using the other pre-determined input parameters, such as α, β, and SFC, it is possible to predict the cargo capacity.

At this stage, a quick assessment of the feasibility of the vessel design could be conducted and would provide insights into the design space and assumptions that need to be changed or areas of improvement necessary to attain the desired outcome.

E. SOURCES OF DATA

The MCMV data used in this thesis was obtained from *Jane’s Fighting Ships*. It is a reliable source for data and analysis on naval and coast guard vessel equipment in development, production, and service around the world. The MCMV data obtained include the nation of origin, vessel class, length, velocity, power, and displacement details. Refer to Table 4 for details.

Table 4. Selected data for MCMVs. Source: Jane's Fighting Ships (2017).

Nation	**Vessel Class**	**Length (ft)**	**Velocity (kts)**	**Power (kW)**	**Displacement (tonnes) (full load)**
U.S.	Independence-class	421.6	40	62200	3188
U.S.	Freedom-class	387.5	40	84900	3462
U.S.	Avenger-class	224.4	13.5	1974	1401
Thailand	Lat Ya (Gaeta)-class	172.2	14	1180	691
Romania	Corsar-class	259.2	19	4900	1473
United Kingdom	Hunt-class	196.9	15	1490	752
Spain	Segura-class	177.2	14	1120	539
Sweden	Visby-class	238.5	35	18600	630
United Kingdom	Sandown-class	172.2	13	1140	546
Taiwan	Yung Ching-class	187.7	10	1180	839
Thailand	Bang Rachan-class	161.1	17	2300	451
Saudi Arabia	Al Jawf (Sandown)-class	172.9	13	1120	488
Singapore	Bedok (Landsort)-class	155.8	15	1170	360
South Africa	River-class	157.5	16	3320	386
Poland	Project 890-class	242.1	14.1	2160	2286
Pakistan	Munsif (Éridan)-class	169.0	15	1370	605
Poland	Goplo (Notec)-class	126.3	14	1470	219
South Korea	Ganggyeong-class	164.0	14	1500	512
Indonesia	Kondor II-class	186.0	17	3240	315
Belgium	Flower-class (Tripartite)	169.0	15	1370	660
Japan	Sugashima-class	177.2	14	1330	599
Denmark	MSF-class	86.9	12	736	127
Malaysia	Mahamiru (Lerici)-class	167.3	16	3000	610
Sweden	Koster-class	155.8	15	1170	400
Denmark	Flyvefiskan-class	177.2	18	4260	488
Russian Federation	Lida (Sapfir)-class	103.3	12	690	137
Turkey	Engin (Circé)-class	167.0	15	1320	518
Sweden	Spårö-class	118.1	13	812	208
Poland	Krogulec-class	190.9	17	1620	599
South Korea	Yangyang-class	194.9	15	2980	923

III. DEVELOPMENT OF THE MATHEMATICAL MODEL

A vessel's performance is primarily dependent on a few fundamental design factors such as length, width, draft, speed, displacement, and power. To better understand if and how these factors are interrelated, the first step in this research was to construct a mathematical model so that the effects of such relationship can be captured. A method was previously established to model the effects of a given volumetric displacement on speeds, ranges, and payloads. This method was adapted using a similar approach to McKesson's best practices curve of plotting the L/D ratio against the volumetric Froude number (Tran 2014).

The term "displacement" is often used in relation to a ship's size but does not effectively define tangible design parameters such as length or width, although it can be generally inferred that a larger ship will most certainly have a larger displacement. The aim of this thesis is to create an alternative model, by defining length as a function of displacement so that a more concrete and intuitive parameter of ship size can be established.

As discussed in the previous chapters, key characteristics that can allow an MCMV to effectively perform its role in MCM strongly depend on its endurance out at sea (measured in range), its movement (measured in speed), and its capacity to carry modules required to execute its tasks (measured in payload). The end goal is then to be able to establish a usable relationship between speed, range, and payload, through the analysis of the MCMV's displacement as a function of its length.

A. ADMIRALTY COEFFICIENT (C) VERSUS VOLUMETRIC FROUDE NUMBER (FN)

An important aspect of the model is the establishment of the relationship between a ship's power and its speed. To establish this relationship required the examination of two key parameters, the admiralty coefficient (c) and volumetric Froude number (Fn). The volumetric Froude number is defined as:

$$Fn_v = \frac{V}{\sqrt{g\nabla^{\frac{1}{3}}}} \tag{1}$$

where V is the velocity (m/s), g is the gravitational constant due to acceleration (m/s^2), and ∇ is the volume displacement (m^3). The admiralty coefficient (*c*) can be expressed by following Tran's methodology of relating the ship's power (P_s), volume displacement and velocity. It is defined as:

$$c = \frac{P_s}{\nabla^{\frac{2}{3}} V^3} \tag{2}$$

The relevant parameters of velocity (m/s), volume displacement (m^3), and power (W) were extracted to generate a range of values of Fn_v and *c*, which was then plotted against each other using the MATLAB program to form a relationship with a generic form of:

$$c = a + \frac{b}{{Fn_v}^m} \tag{3}$$

where a and b are constants derived from the relationship and $m \in [1, 4]$. The resultant plots for each value of power that Fn_v is raised to, denoted by m are shown in Figures 6 through 9.

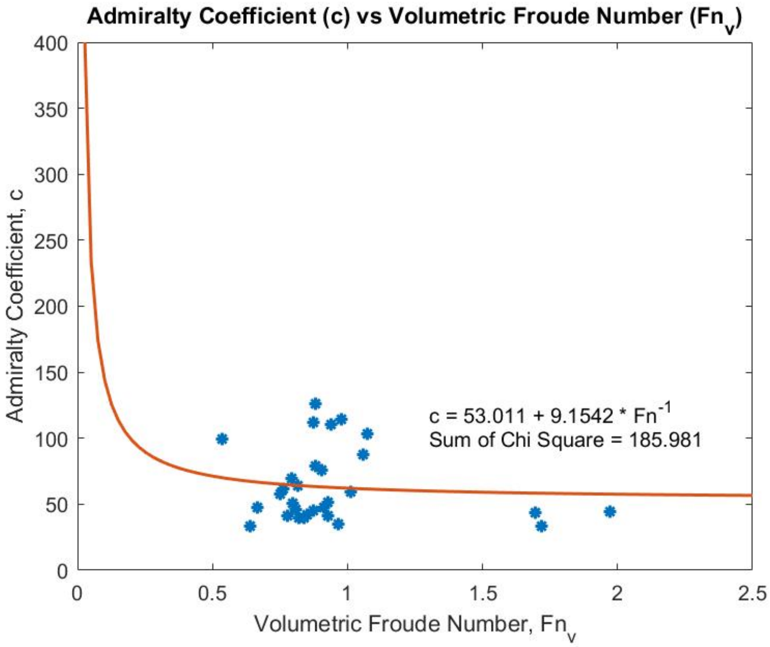

Figure 6. Graph of *c* versus Fn_v for m = 1.

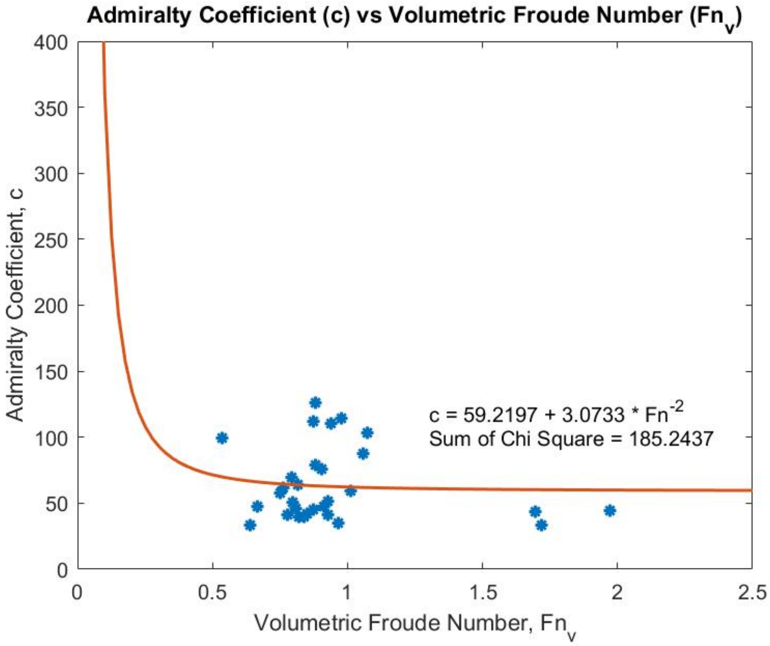

Figure 7. Graph of *c* versus Fn_v for m = 2.

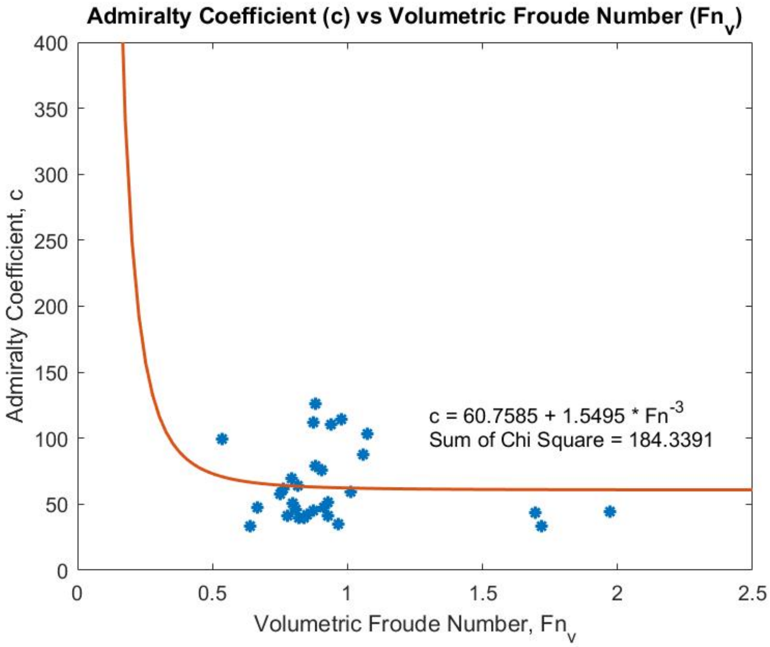

Figure 8. Graph of *c* versus Fn$_v$ for m = 3.

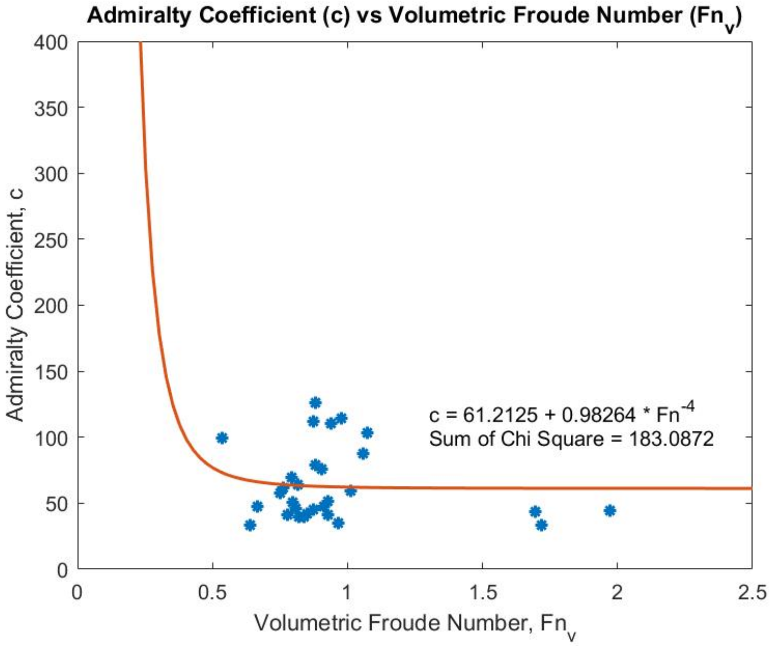

Figure 9. Graph of *c* versus Fn$_v$ for m = 4.

The sum of chi-square, which served as a measurement of error, was calculated by relating the distance of the actual data values against the theoretical curve fit. A smaller sum of chi-square value would signify a better and more accurate fit of the data points. Based on the observed plots, m = 4 produced the lowest sum of chi-square errors. The data points, however, were generally quite scattered from the theoretical curve. In addition, the error term values obtained in all four plots were significantly large and not ideal.

B. ADMIRALTY COEFFICIENT (C) VERSUS FROUDE NUMBER (FN)

Since length was the ideal factor that this thesis would be interested in exploring, another factor known as the Froude number (Fn), which already has length as a function, was utilized and compared. The equation for this factor is defined as:

$$Fn = \frac{V}{\sqrt{gL}} \tag{4}$$

where length is measured in meters. Similarly, the admiralty coefficient (c) was plotted against Froude number (Fn) for the varying m values. The resultant plots are shown in Figures 10 through 13.

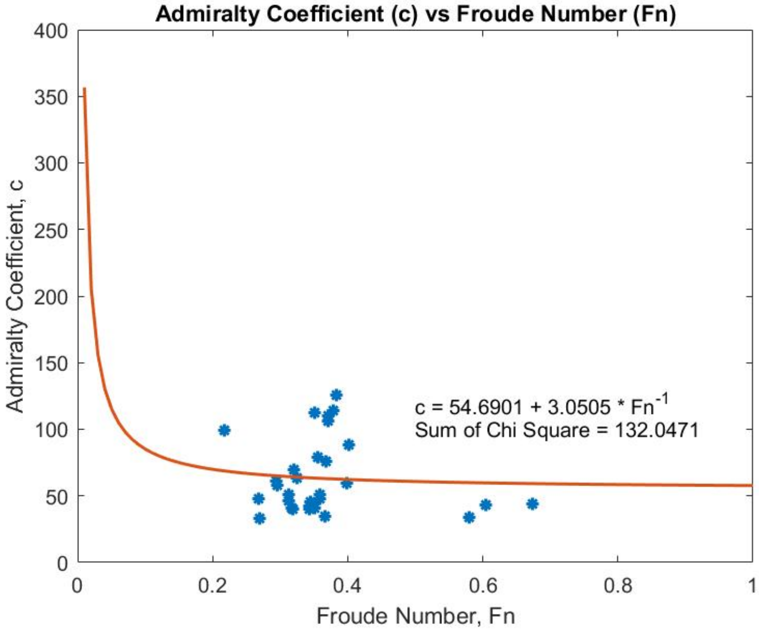

Figure 10. Graph of *c* versus Fn for m = 1.

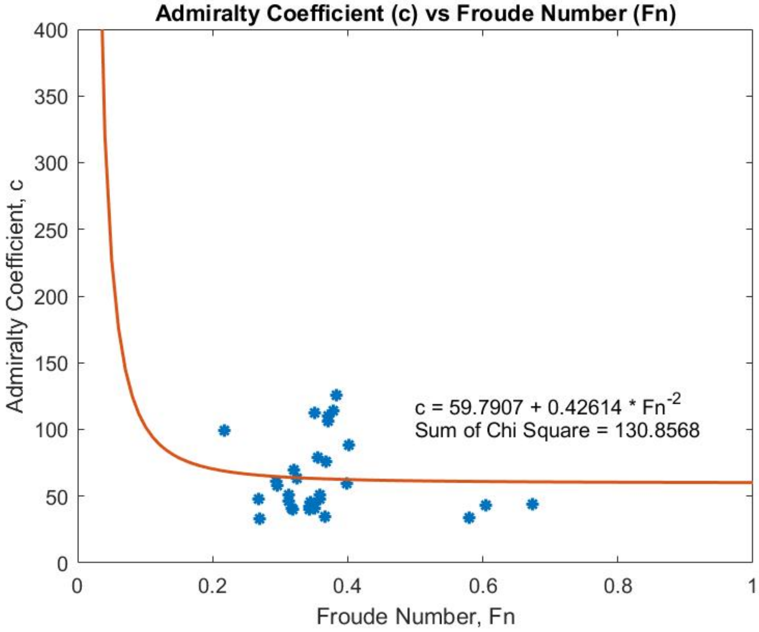

Figure 11. Graph of *c* versus Fn for m = 2.

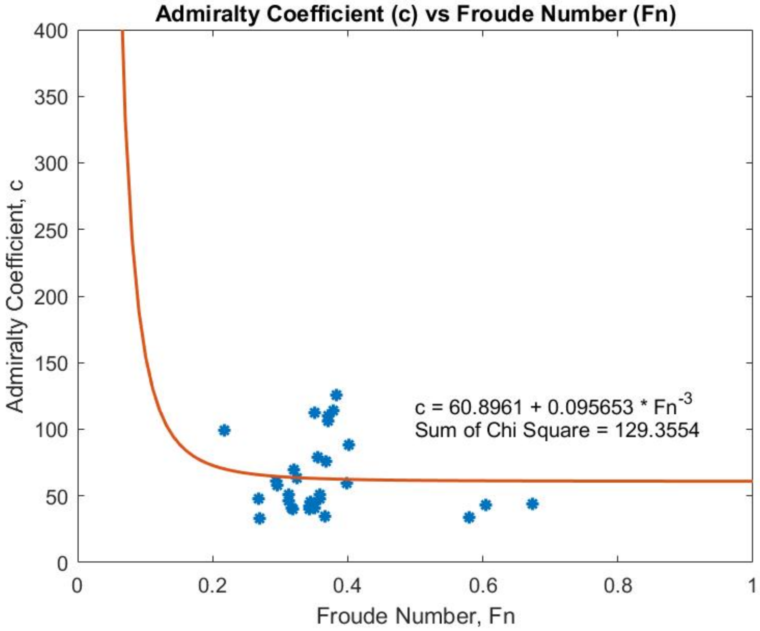

Figure 12. Graph of *c* versus Fn for m = 3.

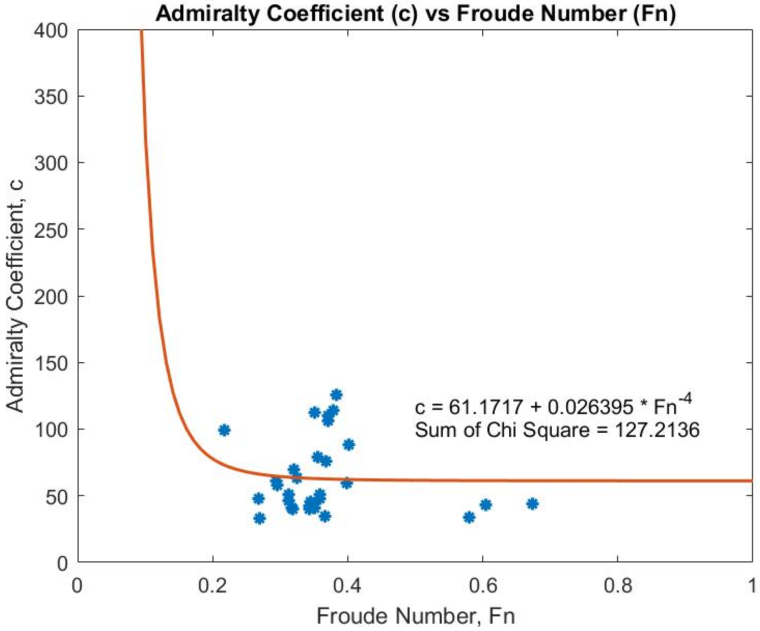

Figure 13. Graph of *c* versus Fn for m = 4.

Based on the plots obtained, an improvement in the model can be seen by the reduced sum of chi-square values across all plots. Nevertheless, the improvements were deemed to be insignificant, with the data points remaining generally scattered. Hence, an alternative approach to constructing the model was considered, involving the establishment of a ship's length as a relationship to its displacement.

C. DISPLACEMENT VERSUS LENGTH

The next step was to establish a relationship between the raw data for length and displacement obtained from the list of MCMVs provided in Table 4. A curve of best fit was generated using EXCEL for the plot of displacement versus length, based on the best R^2 value. It should be noted that the relationship only holds true for the given range of values. Although the data points obtained fall in the range of 30 m to 130 m, the most accurate region is from 30 m to 60 m, where the majority of the points lie. Due to the lack of data points beyond this region (from 80 m to 120 m), the strength of the relationship could not be sufficiently tested for validation. The plot is shown in Figure 14.

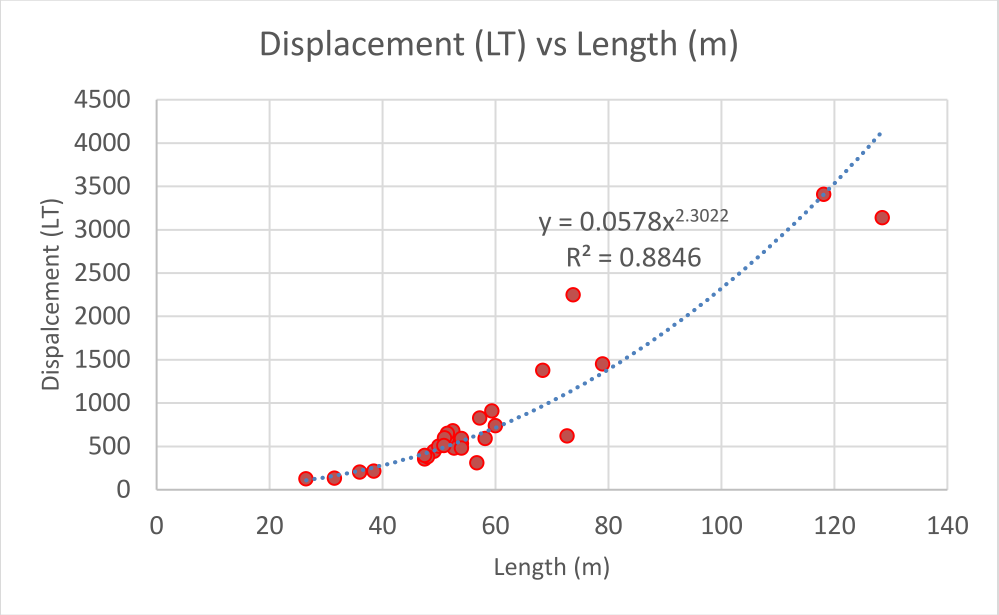

Figure 14. Graph of displacement (LT) versus length (m).

From the plot in Figure 14, the equation establishing the relationship between displacement and length can be written as:

$$\Delta = 0.0578 L^{2.30222} \tag{5}$$

where Δ is the displacement (LT) and L is the length (m). With this relationship established, a range of displacement values was obtained using the series of length data from the MCMV list. A subsequent conversion to volumetric displacement and substitution back into Equation (1) was done to obtain a set of Fn_v values having length defined as a function of displacement. By substituting Equation (5) into Equation (2), it is now possible to define the revised admiralty coefficient term as:

$$c = \frac{P_s}{(\frac{\Delta}{\rho})(V^3)} \tag{6}$$

where ρ is the density of salt water. Once again, the values were plotted, as shown in Figures 15 through 18.

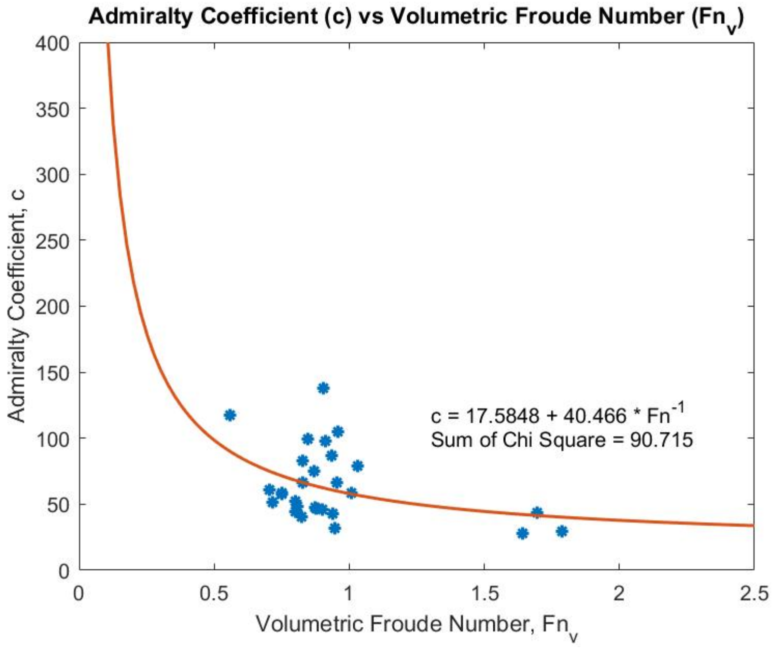

Figure 15. Revised *c* versus Fn$_v$ for m = 1.

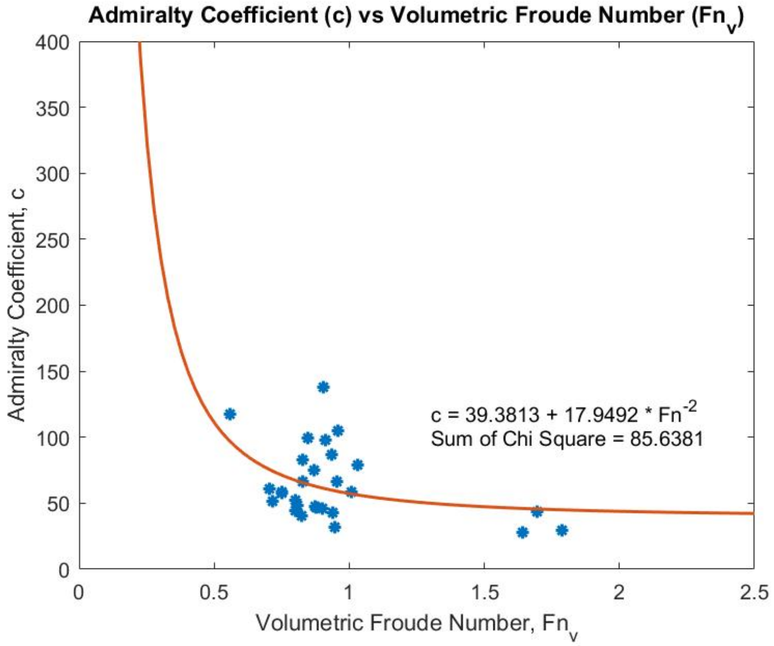

Figure 16. Revised *c* versus Fn$_v$ for m = 2.

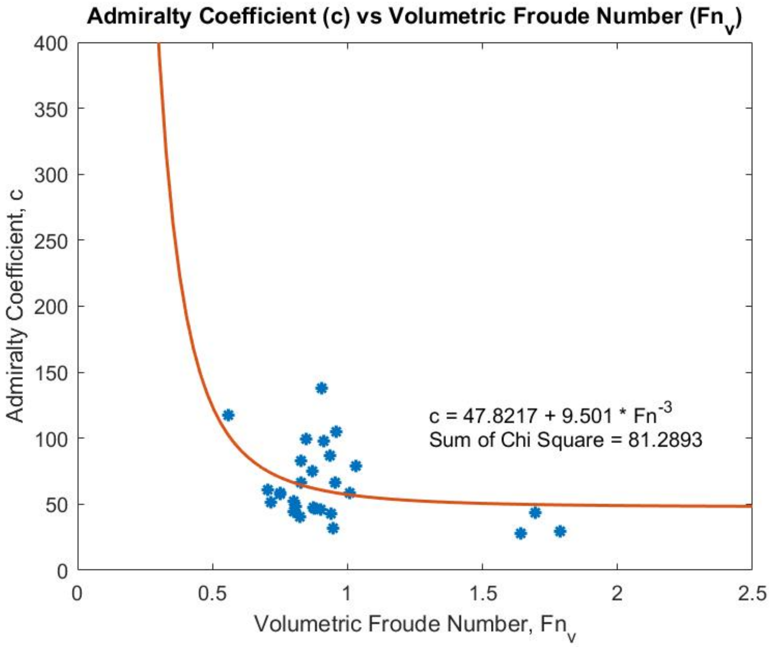

Figure 17. Revised *c* versus Fn_v for m = 3.

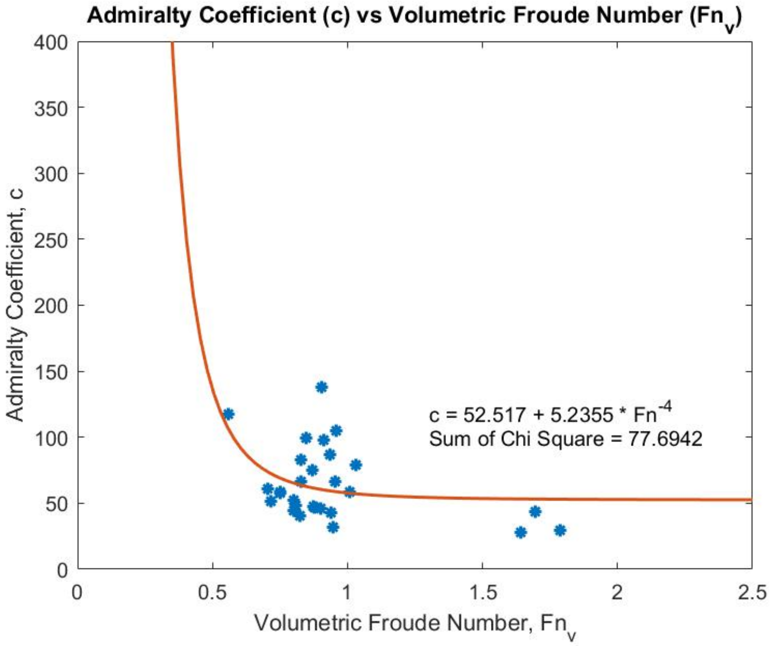

Figure 18. Revised *c* versus Fn_v for m = 4.

Based on the plots from Figures 15 through 18, the newly obtained C and Fn_v values had an even lower sum of chi-square errors, representing that the model was a better fit compared to the previous ones. Yet, comparing these plots with Figures 6 through 9, it was evident the positions of the data points relative to one another had insignificant changes. One potential deduction was that the introduction of a new displacement relationship with respect to length had resulted in at least one other variable having an inaccurate relationship in the equation. In this aspect, the most likely variable affected was the power term P_s, which was only in the admiralty coefficient, but not the volumetric Froude number (Fn_v). Hence, it was necessary to explore a representation of an admiralty coefficient not dependent on the power term, P_s.

D. HARVALD'S ADMIRALTY COEFFICIENT (C)

The admiralty coefficient used in the previous section captures the relationship between the size of the ship (measured by displacement), speed, and the overall power. In 1983, Svend Aage Harvald proposed a formula for the admiralty coefficient (c) that could be used for preliminary ship design (Birk 2019). The admiralty coefficient was intended only as a function of length and speed and was to be used in conjunction with Equation (2) for the estimation of power. The formula the coefficient is defined as:

$$c = 3.7(\sqrt{L} + \frac{75}{V}) \tag{7}$$

Using Equation (7), it was possible to calculate the range of c values solely from the length (m) and speed (m/s) parameters of the MCMV list. The volumetric Froude number was once again plotted against the c values obtained and the results are shown in Figures 19 through 22.

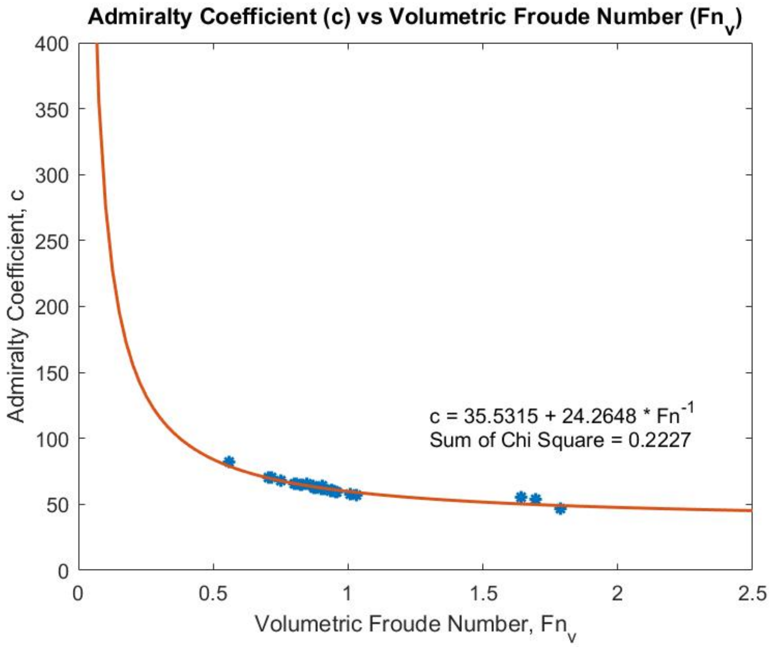

Figure 19. Harvald's *c* versus Fn_v for m = 1.

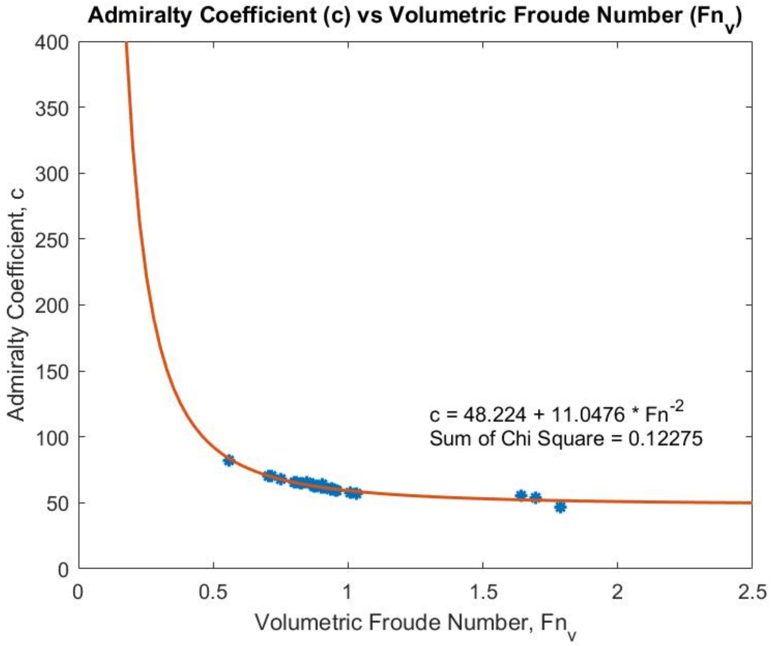

Figure 20. Harvald's *c* versus Fn_v for m = 2.

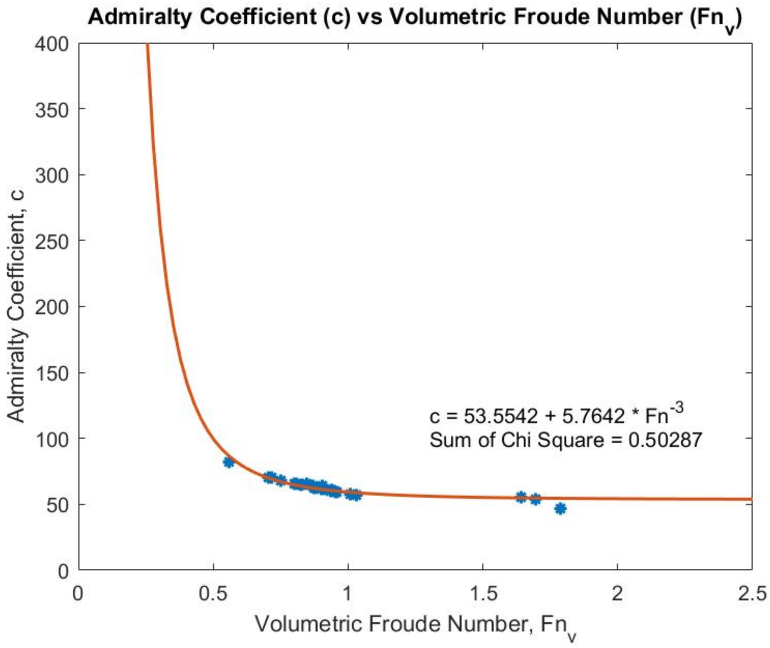

Figure 21. Harvald’s *c* versus Fn_v for m = 3.

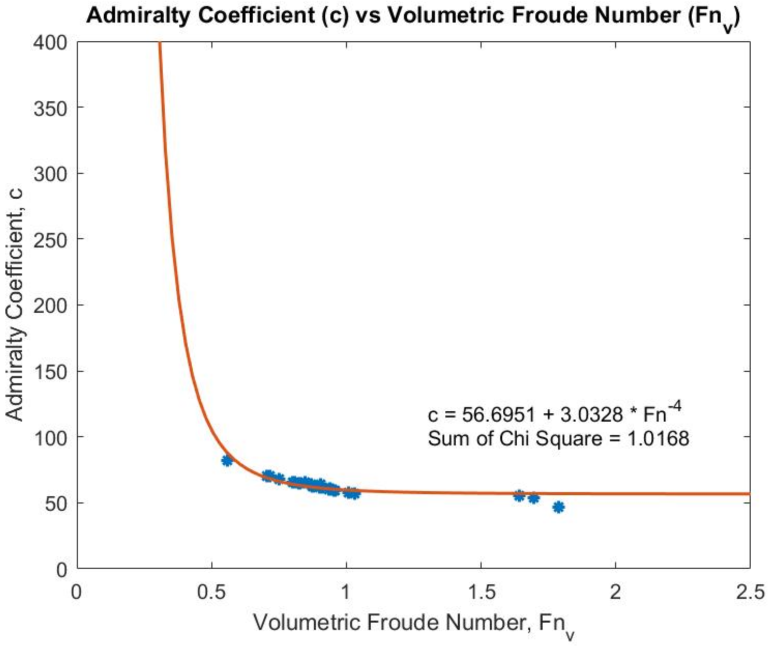

Figure 22. Harvald’s *c* versus Fn_v for m = 4.

Figures 19 through 22 show marked improvements in the model, significantly reducing the sum of chi-square values across all plots to approximately less than 1. The current model obtained with m = 2 (lowest sum of chi-square) was used in the next step in determining the relationship between length, speed, range, and payload.

E. MATHEMATICAL MODEL FOR LENGTH, SPEED, RANGE, AND PAYLOAD TO CALCULATE DISPLACEMENT

Displacement can be used to define a vessel's weight. In general, the displacement can be sub-categorized into three main components: the ship's propulsion system, its fuel, and the rest of the ship (inclusive of cargo) (Tran 2014). The equation for displacement can be represented as:

$$\Delta = \Delta_{prop} + \Delta_{fuel} + \Delta_{cargo} \tag{8}$$

where Δ represents the vessel's total displacement, Δ_{prop} represents the weight of the propulsion system, Δ_{fuel} represents the weight of the fuel, and Δ_{cargo} represents the weight of the remaining ship, including the cargo that it is carrying. The operational performance parameter of interest, payload carrying capacity, can be categorized under Δ_{cargo}, but the term does not solely contain the payload weight; it also includes other aspects not attributable to payload. Hence, to represent the payload weight more accurately, a refinement was made to the term and rewritten as:

$$\Delta_{cargo} = \gamma\Delta + \Delta_{payload} \tag{9}$$

where $\Delta_{payload}$ represents solely the weight of payload and γ represents the proportion of all other weight not attributed to payload, propulsion system, or fuel. In this thesis, the value of γ is first assumed to be 0.4. Following Tran's definition of the sub-categories of total displacement in terms of speed, power, payload, and range, the following equations can be further defined as:

$$\Delta_{prop} = \beta P_s \tag{10}$$

$$\Delta_{fuel} = \frac{(SFC)R}{V} P_s \tag{11}$$

$$\Delta_{c\arg o} = \gamma\Delta + \alpha P \tag{12}$$

where α is the weight of cargo carriage, β is the weight of power, P is weight of payload, R is the range, and SFC is the specific fuel consumption. By substituting Equations (9) through (12) into Equation (8), it is possible to rewrite the displacement equation as:

$$\Delta = \alpha P + \gamma\Delta + \left(\beta + \frac{(SFC)R}{V}\right) P_s \tag{13}$$

Further substitution of Equations (1), (3), and (6) into Equation (13) would thus yield:

$$\Delta = \alpha P + \gamma\Delta + \left(\beta + \frac{(SFC)R}{V}\right)\left(a + b\frac{g}{V^2}\left(\frac{\Delta}{\rho}\right)^{\frac{1}{3}}\right)\left(\frac{\Delta}{\rho}\right)^{\frac{2}{3}} V^3 \tag{14}$$

A further substitution of Equation (5) into Equation (14) now yields an equation that ties in the relationship between terms of the variables L, V, R, and P.

IV. SUMMARY OF MATHEMATICAL MODEL

The aim of establishing a mathematical model is to have an equation that accurately validates the relationship of ship design input parameters such as L, V, R, and P to one another and to obtain useful output such as displacement. Without the need for time-consuming and comprehensive software analysis, the mathematical model serves as a preliminary tool for determining what is feasible in the design of a ship and what is not, and can potentially save time and streamline processes that are costly. By varying values of displacement obtained (due to varying L), it is possible to establish the effects of these changing values on V, R, and P.

A. SUMMARY OF KEY EQUATIONS AND INPUT PARAMETERS

The basis of the mathematical model is dependent on the initial relationship established between vessel length and its displacement, shown in Equation (5). Equation (14) captures the important relationship between interacting coefficients and parameters to obtain the resultant displacement value. The two key equations are as shown:

$$\Delta = 0.0578L^{2.30222} \tag{15}$$

$$\Delta = \alpha P + \gamma\Delta + \left(\beta + \frac{(SFC)R}{V}\right)\left(a + b\frac{g}{V^2}\left(\frac{\Delta}{\rho}\right)^{\frac{1}{3}}\right)\left(\frac{\Delta}{\rho}\right)^{\frac{2}{3}}V^3 \tag{16}$$

A summary of required input parameters and variables follows:

- **L** Vessel length is measured in meters (m) – One meter = 3.28 feet.
- **V** Vessel speed is measured in meters per second (m/s) – 1 nautical mile per hour = 0.5144m/s.
- **R** Vessel range is measured in nautical miles (nm).

- **P** Vessel payload is measured in long tons (LT). Payload refers to the MCM modules or system that the vessel is carrying.

- **α** Cargo Carriage Multiplier – Measured in long tons/long ton, this refers to “the weight of the shopping bag into which the cargo is put” (McKesson 2010). The assumed value of 2 long tons/long ton of cargo is used for military vessels such as the MCMV in this model.

- **β** Weight of Power is measured in lbs/hp and refers to the weight of the propulsion plant on the vessel, including propulsors and engines, but excluding the weight of the fuel. The assumed value of 10 lbs/hp is used for military vessels such as MCMV in this model.

- **γ** This refers to the proportion of all other weight not related to payload, propulsion system, or fuel. The value of 0.4 is assumed in this thesis.

- **a** & **b** These coefficients are derived from plotting the admiralty coefficient (c) against the volumetric Froude number (Fn_v).

- **SFC** Specific Fuel Consumption – It is the overall fuel consumption of the machinery, measured on a specific or per-horsepower-hour basis. The value of 0.33 lbs/hp-per-hour is assumed here.

- **g** The gravitational constant is set at a value of $9.8\ m/s^2$.

- **ρ** This represents the density of seawater, which is set at a value of $1025\ kg/m^3$.

Once the required variables and coefficients were derived and assumed, they were used as input parameters for Equation (14) to generate a displacement value. The summary of the key steps to establish the model are:

1. Select the desired ship design parameter values of L, V, R, and P.

2. Input the pre-determined predictor values of α, β, γ, SFC, a, and b.

3. Generate the displacement value and obtain the relationship between V, R, and P.

4. Vary values in steps (1) and (2) to obtain a range of displacement values and study their effects on V, R, and P.

B. GENERAL SPEED, RANGE, AND PAYLOAD RELATIONSHIP FOR A GIVEN DISPLACEMENT

Following the steps illustrated and selecting the values required, it is possible to calculate displacement. As an example, the following values of the variables and coefficients in were used:

- L = 100 m
- V = 40 kts
- R = 3000 nm
- P = 400 LT
- α = 2 long tons/long ton
- β = 10 lbs/hr
- γ = 0.4
- a = 48.224
- b = 11.0476
- SFC = 0.33 lbs/hp-per-hour
- g = 9.81 ms^2
- ρ = 1,025 kg/m^3

where the calculated displacement was found to be 3361 LT using the MATLAB program. In addition, the effects on V, R, and P for the given displacement value were established as shown in Figure 23.

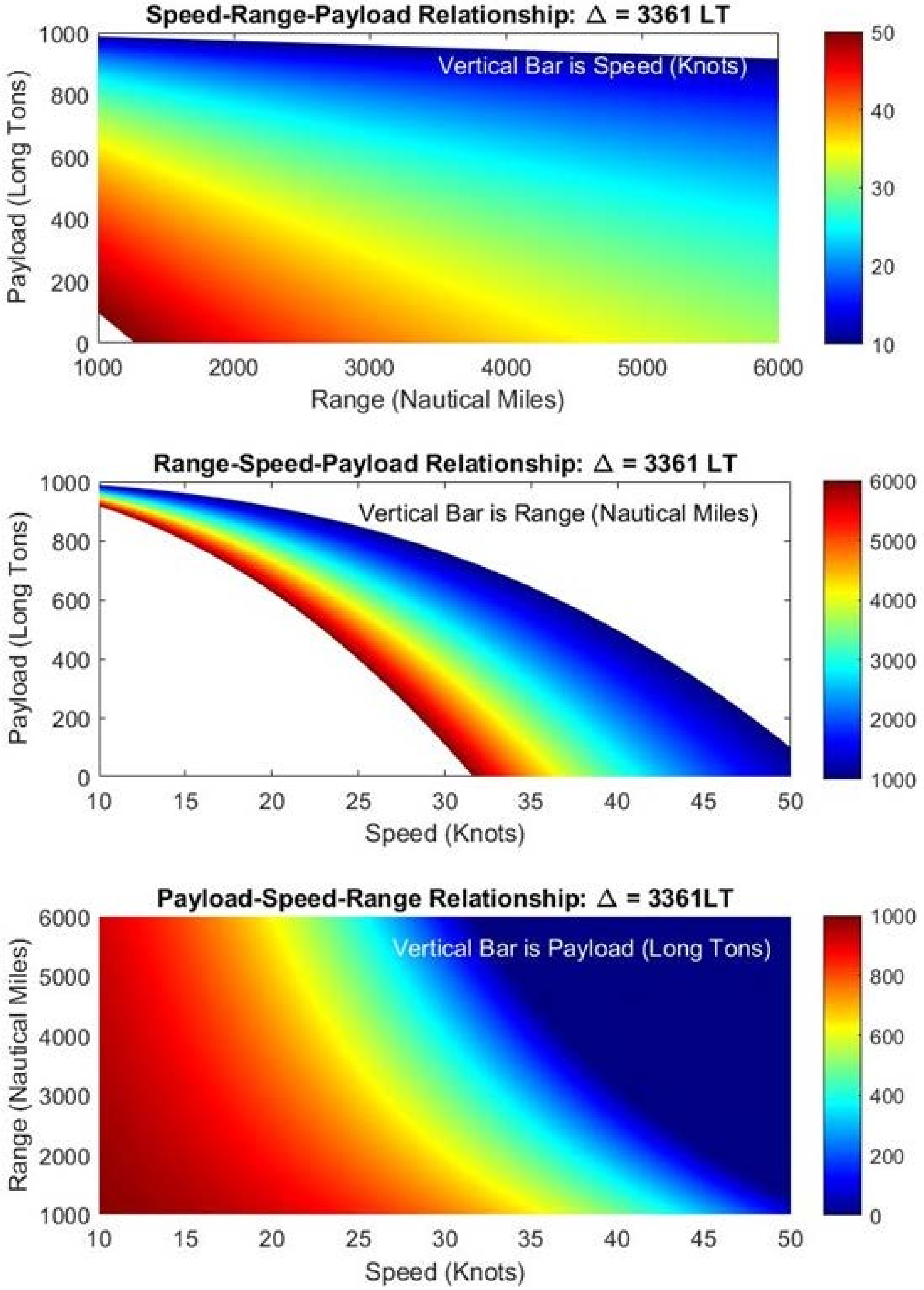

Figure 23. Speed, range, and payload relationship plots.

The plot in Figure 23 shows that as range or payload increases, the speed of the ship will decrease, which is a logical and acceptable conclusion. Similarly, as payload or speed increases, range decreases. This is also acceptable given the fact that when a ship is moving at higher speeds, its consumption of fuel increases non-linearly, and hence results in less fuel for a longer range. Interestingly, however, the magnitude of range differences changes significantly with varying payloads. At a high payload of 900 LT, increasing speed results in a greater decrease in range, and at a low payload of 200 LT, increasing speed results in a smaller decrease in range. This could serve as a model to understand the consequence on range (which is a measurement of endurance out at sea) for specific payloads at varying speeds. Another logical finding is that as range or speed increases, the payload decreases.

C. VALIDATING THE MODEL

The next step was to validate the model against known MCMV specifications and to evaluate the model fit. The two vessels chosen for this purpose were the LCS 1 (Freedom Class) and the MCM Design Vessel by NSWCCD. These vessels have the specific parameters, such as range, velocity, length, and most importantly, sufficient details available on the payload weight that enabled valid assumptions for comparisons. The payload weight of the LCS 1 Freedom was assumed to be the maximum MCM payload weight that the LCS 1 Seaframe could carry (Committee on Appropriations 2010). As there was no direct MCM payload weight given for the MCM Design Vessel, this was calculated by summing up the weight of relevant systems that are not attributed to fuel, propulsion, or structures (Galante 2013). The calculated full load displacement values of the model are shown in Table 5.

Table 5. Model calculated displacement values compared to actual displacement values with original parameters.

α = 2 long tons/long ton, **β** = 10lbs/hr, **γ** = 0.4, **SFC** = 0.33 lbs/hp-per-hour		
Vessel Type	**LCS 1 (Freedom Class)**	**MCM Design Vessel (NSWC)**
Range (nm)	3500	50
Speed (kts)	14	8
Payload (LT)	207	62
Length (m)	118.1	54.9
Actual Displacement (LT)	3407	602
Model Calculated Displacement (LT)	2148	361
Percentage Difference (%)	36.95	40.03

The calculated displacement values for both vessels were significantly lower than the actual displacement values given in the literature. To improve the model, adjustments were made to three parameters by increasing the α value from 2 to 4 long tons/long ton, increasing γ value from 0.4 to 0.6, and increasing the SFC value from 0.33 to 0.4 lbs/hp-per-hour.

Table 6. Model calculated displacement values compared to actual displacement values with adjusted parameters.

α = 4 long tons/long ton, **β** = 10lbs/hr, **γ** = 0.6, **SFC** = 0.40 lbs/hp-per hour		
Vessel Type	**LCS 1 (Freedom Class)**	**MCM Design Vessel (NSWC)**
Range (nm)	3500	50
Speed (kts)	14	8
Payload (LT)	207	62
Length (m)	118.1	54.9
Actual Displacement (LT)	3407	602
Model Calculated Displacement (LT)	3314	602
Percentage Difference (%)	2.73	0

With the adjustments to the parameters made, there were significant improvements to the model, with differences of less than 3 percent obtained. This could be attributed to the fact that both the initial α value of 2 and γ value = 0.4 could have been underestimated. For military vessels like the MCMV, due to potential enhancements made to hull structures for added protection against mine threats, there would inevitably be an increase in the α value. Hence, using $\alpha = 4$ would have been be an acceptable explanation. In addition, the $\gamma = 0.4$ was only used as an estimate, and an increase in γ would signify that the proportion of all other weight not related to payload, fuel, or propulsion system is higher. This is aligned with the fact that the increased weight potentially due to enhanced hull structures would naturally result in an increase in α and increase in γ. The initial SFC value of 0.33 lbs/hp-per-hour, which was assumed by predicting the downward trend of SFC value over the years, might have been overestimated. Both the design and conceptualization of the LCS 1 (Freedom class) and MCM Design Vessel occurred in the early 2010s, and hence, the improvements to the SFC based on advances in engine technology might not have been that significant. A more conservative value of 0.40 lbs/hp-per-hour, which would more likely be reasonable, was hence adopted instead.

With the adjusted parameters, the effects on V, R, and P were replotted as shown in Figure 24. Based on the plots obtained, it was observed that the general relationships between V, R, and P were maintained, although the feasible payload range was significantly reduced. This was due to the increase in α and γ values, which increased the weight of other non-payload factors, and thereby decreased the allowable payload weight possible.

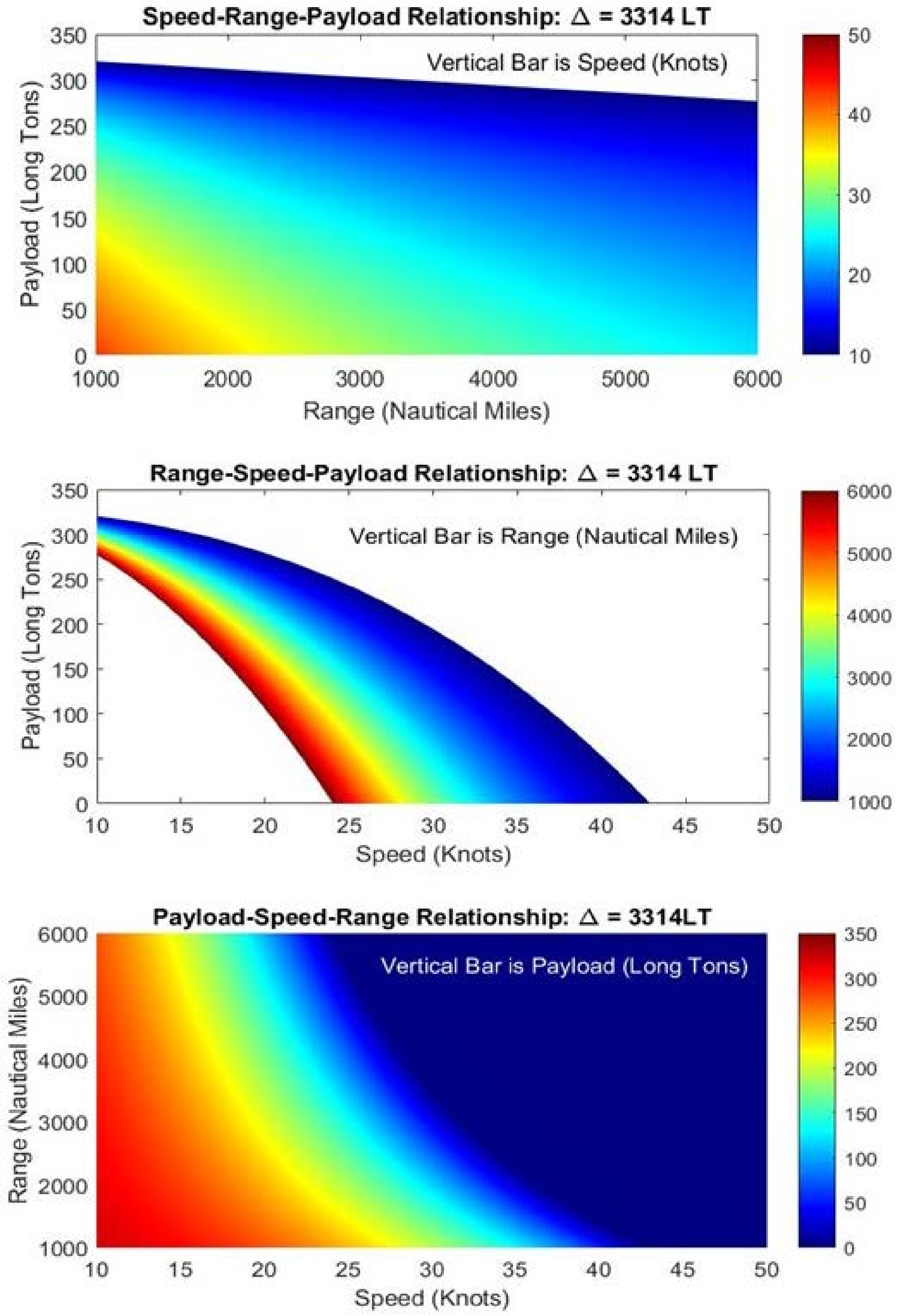

Figure 24. Speed, range, and payload relationship plots with adjusted parameters.

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V. SENSITIVITY ANALYSIS

The input parameter values to the model such as the cargo carriage multiplier (α); weight of power (β); proportion of all other weight not related to payload, propulsion system, or fuel (γ); and specific fuel consumption were selected based on previous studies conducted. Over time, these input parameter estimates will likely change or be refined during the vessel design process and as technology improves. It is thus imperative to understand how changes might affect these values and to what extent such changes could affect the output of the model such as displacement, speed, range, and payload. To that end, sensitivity analysis was conducted using the LCS 1 (Freedom Class) vessel as the basis of comparison.

A. SENSITIVITY ANALYSIS ON DISPLACEMENT VALUE OF OUTPUT

By varying the input parameters through suitable and realistic intervals in the MATLAB program code, it was possible to generate different output displacement values. The percentage difference was obtained by subtracting the new displacement value from the original displacement value of 3314 LT based on the initial fixed set of input parameters. A sensitivity ratio was then calculated to indicate the required change in units for the input parameter to produce a 1-unit change in displacement. The respective data for the sensitivity analysis done on the output displacement value is shown in Table 7. By comparing the sensitivity ratios obtained for the different input parameters, it was determined that γ is the most sensitive input parameter followed by α, SFC, and lastly β, which is the least sensitive. For every 1.62-unit change in γ, there is a 1-unit change in the displacement value and likewise for β, an 83.3-unit change is required to change 1-unit in displacement value. This is evident in the difference in gradient steepness for the various input parameters shown in Figure 25.

Table 7. Displacement values calculated for changes in input parameters.

	Cargo Carriage Multiplier (α)		
	4	**3**	**2**
Percentage Change (%)	-	25	50
Displacement	3314	3107	2900
Percentage Difference (%)	-	6.25	12.50
Sensitivity Ratio	**1:4**		

	Weight of Power (β)			
	20	**15**	**10**	**5**
Percentage Change (%)	100	50	-	50
Displacement	3354	3334	3314	3294
Percentage Difference (%)	1.20	0.60	-	0.60
Sensitivity Ratio	**1: 83.3**			

	Proportion of all other weight not related to payload, propulsion system, or fuel (γ)				
	0.60	**0.55**	**0.50**	**0.45**	**0.40**
Percentage Change (%)	-	8.33	16.67	25	33.33
Displacement	3314	3144	2973	2803	2633
Percentage Difference (%)	-	5.13	10.29	15.42	20.54
Sensitivity Ratio	**1: 1.62**				

	Specific Fuel Consumption (SFC)				
	0.40	**0.38**	**0.36**	**0.34**	**0.32**
Percentage Change (%)	-	5	10	15	20
Displacement	3314	3294	3274	3254	3234
Percentage Difference (%)	-	0.60	1.21	1.81	2.41
Sensitivity Ratio	**1: 8.3**				

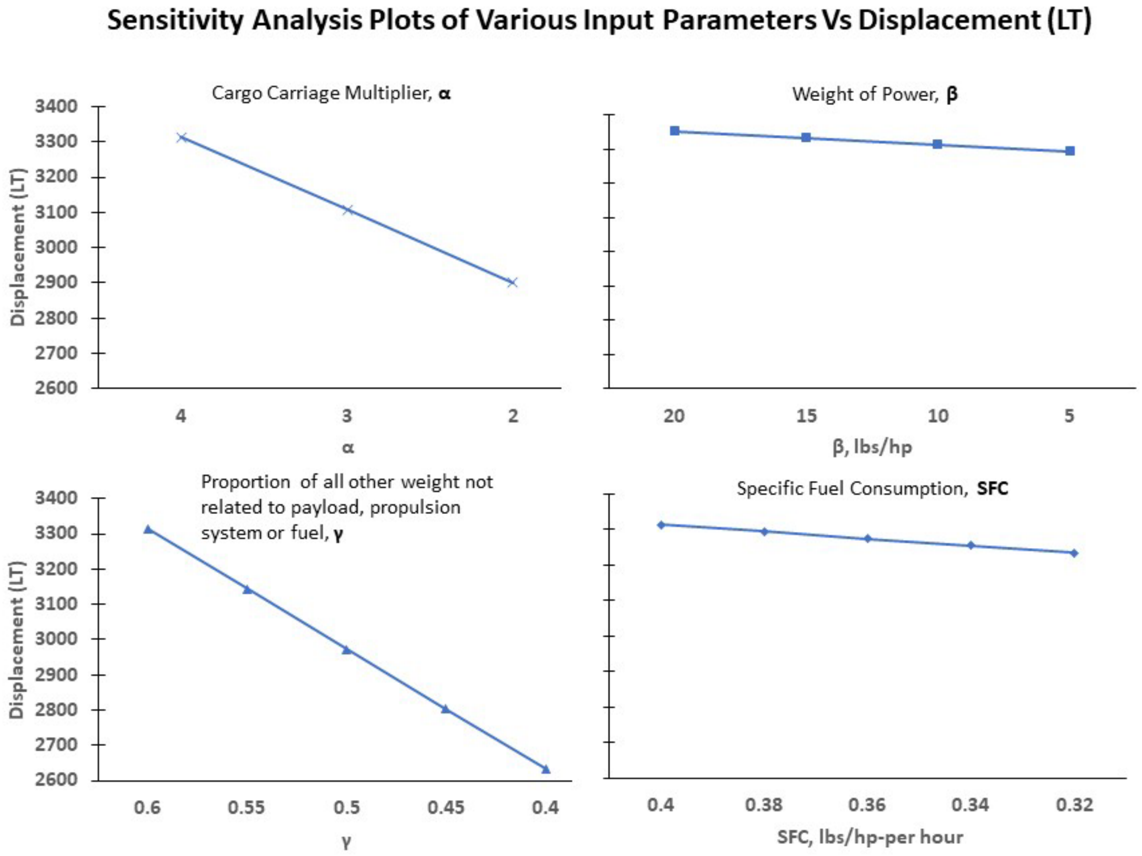

Figure 25. Sensitivity analysis plots of various input parameters versus displacement (LT).

B. SENSITIVITY ANALYSIS ON GENERAL RELATIONSHIP BETWEEN SPEED, RANGE, AND PAYLOAD

The speed, range, and payload relationship plots were generated by varying displacement values obtained from the model based on a set of input parameters. It is also of interest to understand how and to what extent the changes in these input parameters affect the relationship between speed, range, and payload, given a fixed displacement. Figures 26 through 29 show the speed, range, payload plots for the respective changes to input parameters α, β, γ, and SFC.

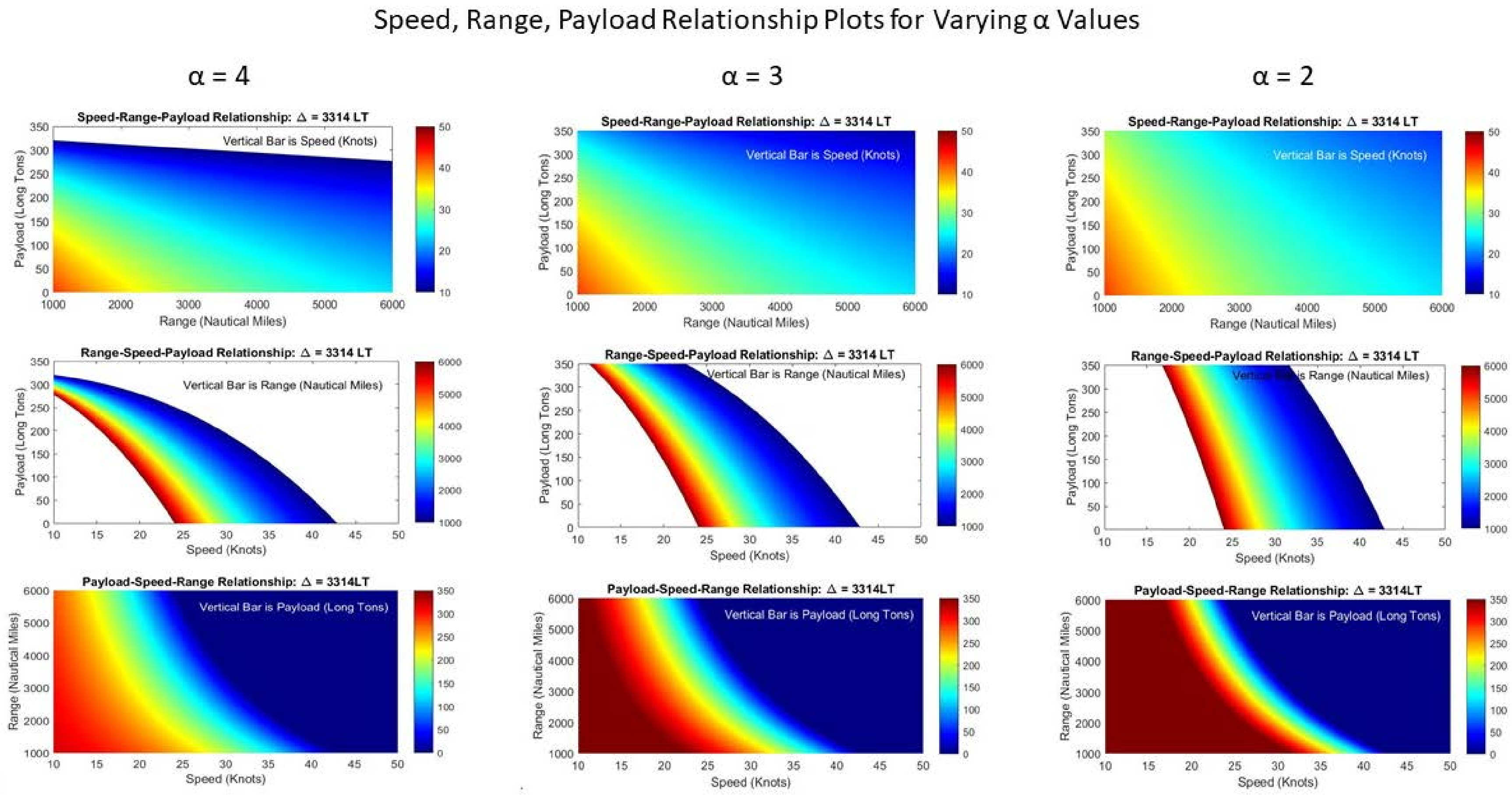

Figure 26. Speed, range, payload relationship plots for α = 4, 3, and 2.

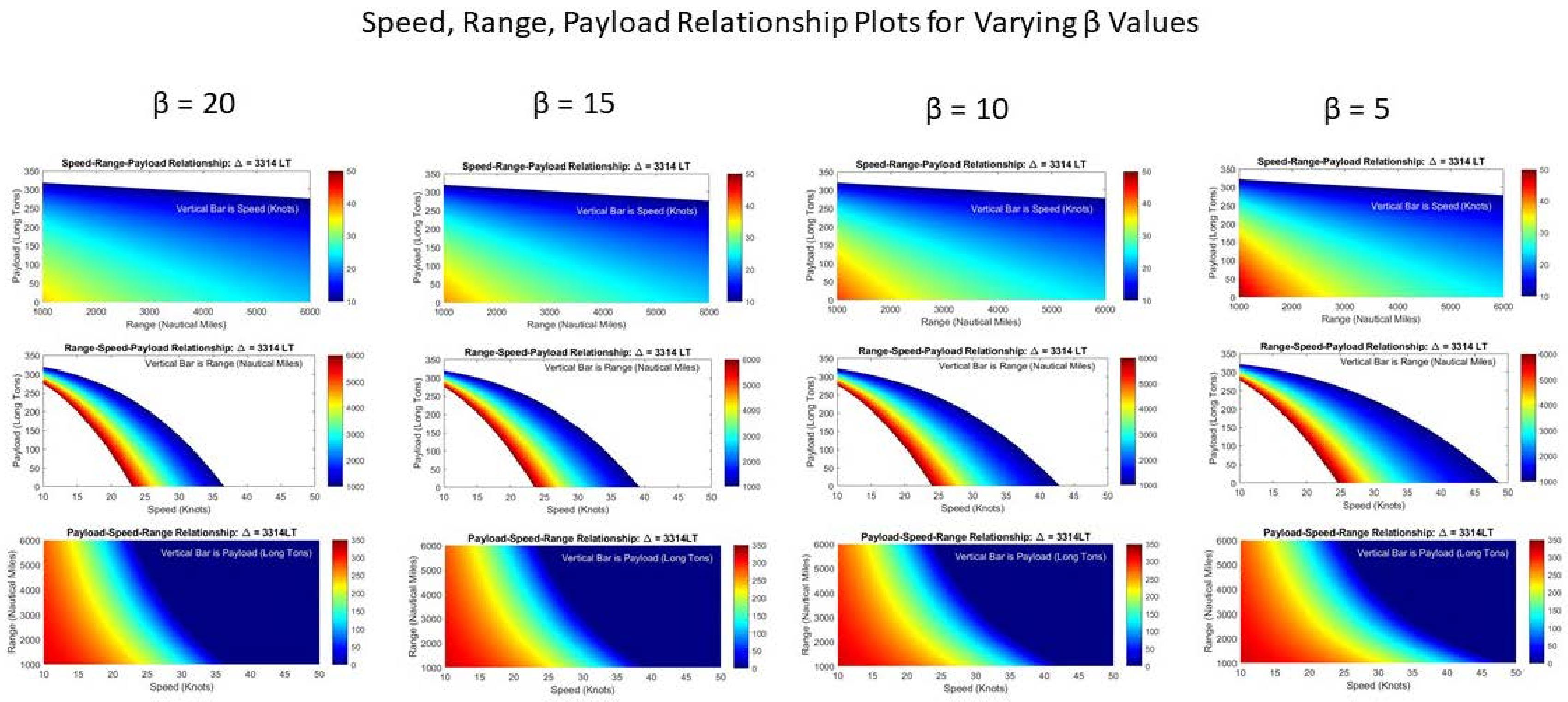

Figure 27. Speed, range, payload relationship plots for β = 20, 15, 10, and 5.

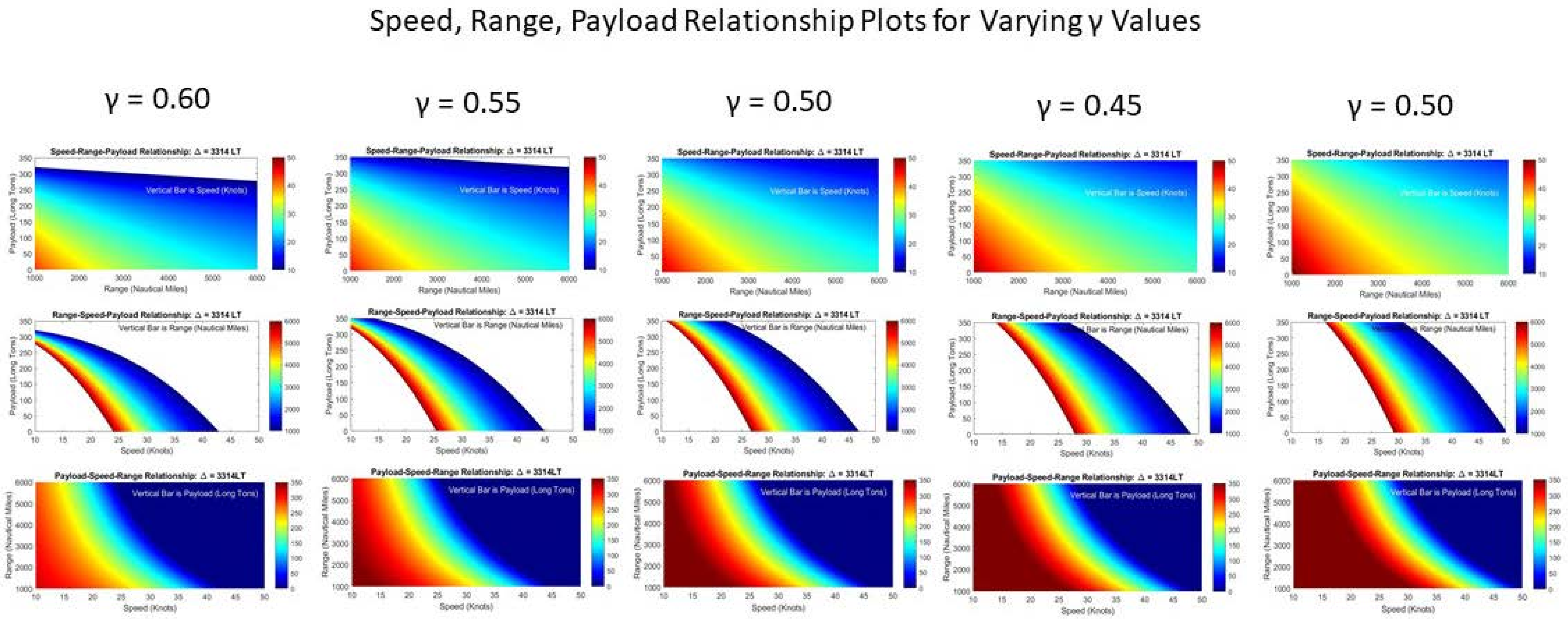

Figure 28. Speed, range, payload relationship plots for γ = 0.60, 0.55, 0.50, 0.45, and 0.40.

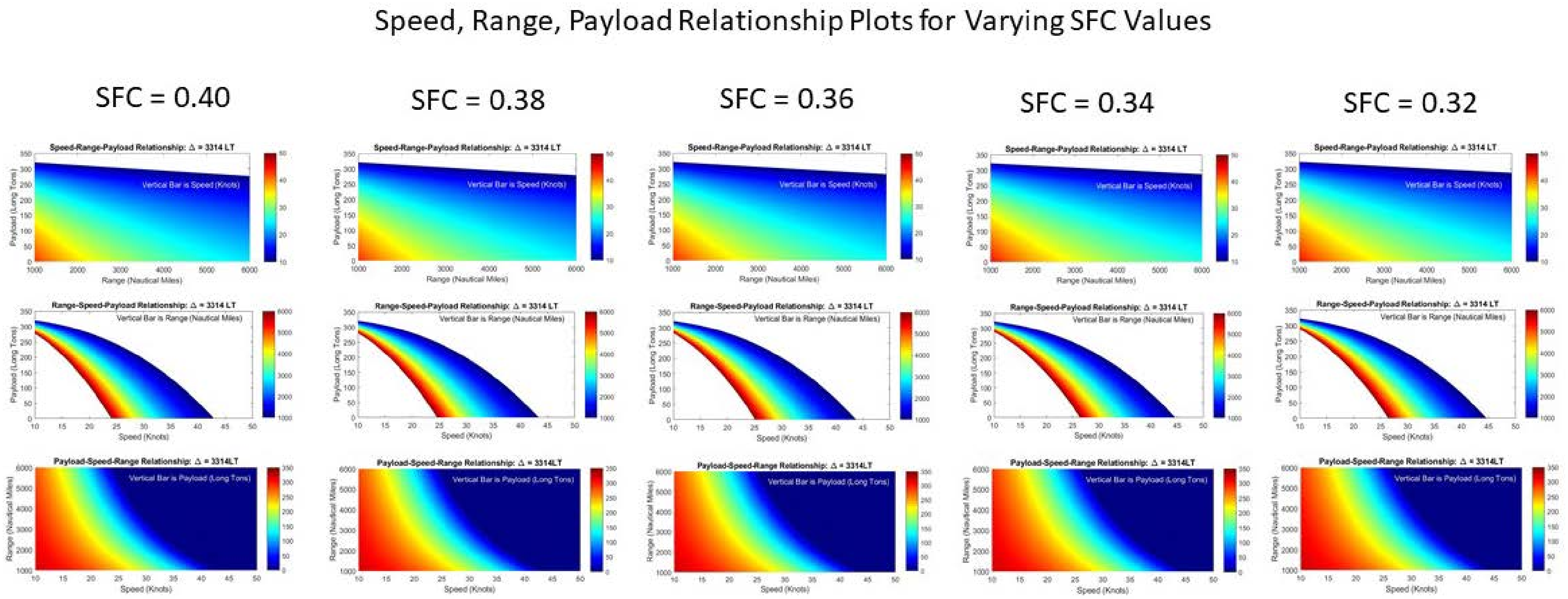

Figure 29. Speed, range, payload relationship plots for SFC = 0.40, 0.38, 0.36, 0.34, and 0.32.

1. Effects of Varying α

Varying the α value changes the weight of the "carriage" required to contain its cargo. Thus, when the α value decreases from 4 to 2, the ratio of "carriage" to "cargo" decreases and results in a higher capacity for carrying payload. This is evident in Figure 26, as the feasible region of payload capacity significantly increases, ceteris paribus. The α value, which is the vessel design dependent, is thus a critical indicator to consider when considering payload capacity. This is especially so for naval vessels such as the MCMV, where enhanced hull protection used for passive MCM is a necessity and would contribute to increasing α values. Tradeoffs between protection in defensive MCM against payload capacity for offensive MCM will need to be analyzed and studied in detail for a fine balance to be achieved.

2. Effects of Varying β

Varying the β value changes the weight taken up by the propulsion system (less fuel) to produce a required power. A lower β value is more ideal, as it would imply less weight taken up by the propulsion system (less fuel) to produce the same amount of power. This is supported by Figure 27, where a β value of 5 significantly increases the feasible ranges of speed (broadening effect of the spectrum), indicating an increase in speed flexibility for a desired range. This occurrence, however, is more evident in lower ranges (< 3000 nm). Conversely, a higher β value of 20 narrows the feasible speed range. A tradeoff between decreased range and an increased speed could be complemented by incorporating systems such as UUVs to maintain MCM effectiveness when designing future MCMVs.

3. Effects of Varying γ

Varying the γ value changes the proportion of all other weight not related to the payload, propulsion system, or fuel. This proportion would mainly consist of weights such as hull structures, and outfit and furnishings, as categorized by the Ship Work Breakdown Structure (SWBS) (Moore and Clapham 1996). Similar to the effects of varying α, a lower

γ value would imply a higher payload capacity, as shown in Figure 28. Changes in the γ value would also be a critical vessel design indicator for the consideration of tradeoffs involving payload capacity. In addition, a decrease in γ value would generally decrease the overall weight of the vessel and allow for a higher range of feasible speeds. As shown in Figure 28, for payload weight = 0LT, the maximum allowable speed for the vessel to travel 6000 nm was 30 kts when $\gamma = 0.50$ as compared to 25 kts when $\gamma = 0.60$.

4. Effects of Varying SFC

Varying the SFC value changes the fuel consumption efficiency of the vessel engine in operation, where a lower SFC value is more ideal as it improves a vessel’s performance in speed and range. This is shown in Figure 29, where for a given range, the feasible speed has increased. Nevertheless, the improvement was not significant, even when SFC values improved from 0.40 to 0.32. This shows that SFC was not a critical vessel design indicator and changes to this value had minimal impact in terms of resultant tradeoffs.

C. SUMMARY OF SENSITIVITY ANALYSIS

From the sensitivity analysis conducted, it was observed that the cargo carriage multiplier, α, had a sensitivity ratio of 1:4 on displacement. As the α value decreases, displacement decreases as well, due to a lower vessel weight attributed to the lower α value. In this regard, the payload capacity could be increased by initiating tradeoffs in terms of decreasing defensive MCM measures.

The weight of power, β, had the greatest effect on the feasible speed for ranges less than 3000 nm. To achieve the best effect of reducing the β value, vessel range would have to be significantly decreased, but could be made up for by incorporating UUVs for enhanced range. The β value had a sensitivity ratio of 1: 83.3, indicating that there was little or almost no impact to displacement values.

By decreasing the proportion of all other weight not related to payload, propulsion system, or fuel, γ value, it is possible to increase payload capacity together with improving speed ranges. The γ value had a sensitivity ratio of 1: 1.62, which was the most the sensitive input parameter, as was shown by the fact that changing γ had the greatest impact on displacement.

By contrast, the SFC value had minimal or no impact to improvements in speed, range, or payload. With a sensitivity ratio of 1: 8.3, displacement decreases with decreasing SFC value. Given the current estimated range of SFC values is between 0.30 to 0.40 lbs/hp-per-hour, based on McKesson’s study and prediction trend, there are no significant impacts on displacement, speed, range, or payload. With improvements in technology in the future, this value could be sufficiently improved to impact vessel design parameters.

VI. CONCLUSION AND RECOMMENDATIONS

The aim of this thesis was to explore MCMV design parameters that would affect the vessel's operational performance in the terms of speed, range, and payload capacity. By using a tangible and intuitive vessel design parameter such as length, this thesis research established a usable relationship between that parameter and its displacement. In this process, a mathematical model was created that could relate MCMV length to its speed, range, and payload capacity. The results obtained from the mathematical model served as preliminary insights for determining feasible ranges of MCMV design parameters. Moreover, this thesis research has shown that the MBSE approach can be used to link vessel design parameters to their operational performance. This success could be potentially expanded to other types of operational vessels.

The effects of other important design parameters such as cargo carriage multiplier (α); weight of power (β); and proportion of all other weight not related to payload, propulsion system, or fuel (γ) were also considered and analyzed. Because these design parameters do not pertain solely to MCMVs but to all types of vessels, the study of these design parameters provide meaningful insights about their impact on displacement, speed, range, and payload capacity. These parameters could be used as preliminary considerations to enhance operational performance when designing future MCMVs.

Several recommendations for future work emerge from the findings of this thesis. The approach of this research centered on static MCM systems available on the vessel that affect displacement, speed, range, and payload capacity. A recommendation would be to also explore the analysis of UUVs or USVs, which comprise a common MCM system in many MCMVs today. The introduction of these unmanned systems would most certainly change the operational concept of the MCMV and its design parameters to achieve a desired performance.

In this thesis, payload was defined to be the MCM module or system required for the MCMV to carry out its operational mission. In this aspect, the availability of payload weight is important to relate its effects more accurately on displacement, speed, and range.

Unfortunately, there was no readily available weight data on the MCM subsystems, and the overall payload weight could only be estimated. This value could be further refined to get a better estimate as the MCM systems to be incorporated become known and their associated data is published.

Furthermore, the developed model relied on a limited number of MCMV data points to establish a relationship between the MCMV length and its displacement. The data points were selected based on the different available classes of MCMV that could be found in open sources. Although the thesis research aimed to use various classes for the developed model, it was limited to the number of data points available. A wider range of MCMV data points would significantly improve the robustness of the model, by obtaining a better fit that describes the relationship.

The results obtained in this thesis have proven that efforts in using MBSE to construct simple models can allow for effective representation of relationships in vessel design. In the words of McKesson (2011, 6):

> In the same way that great artists can depict an entire human figure with only a few sweeping curves, so can the complex engineering systems be usefully modeled on the basis of a Very Simple representation…. Sometimes simple is beautiful.

LIST OF REFERENCES

Axe, David. 2019. “America Is Getting Rid of Their Minesweepers.” *The National Interest* (blog), April 3. https://nationalinterest.org/blog/america-getting-rid-their-minesweepers-50552.

Birk, Lothar. 2019. “Resistance Estimates - Guldhammer and Harvald’s Method.” In *Fundamentals of Ship Hydrodynamics: Fluid Mechanics, Ship Resistance and Propulsion*, 367–368. Hoboken, NJ: John Wiley & Sons.

Camacho, M., D. Galindo, D. Herrington, T. Johnson, A. Olinger, J. Sovel, W. Stith, J. Wade, P. Walker. 2017. “Investigation of Requirements and Capabilities of Next-Generation Mine Warfare Unmanned Underwater Vehicles.” Masters capstone project report, Naval Postgraduate School.

Eckstein, Megan. 2017. “Littoral Combat Ship Program Vastly Different a Year into Major Organizational, Operational Overhaul.” USNI News. September 6, 2017. https://news.usni.org/2017/09/06/littoral-combat-ship-program-vastly-different-year-major-organizational-operational-overhaul.

Sherman, Robert. 1999. “Concept for Future Naval Mine Countermeasures in Littoral Power Projection.” Military Analysis Network. December 7, 1999.https://fas.org/man/dod-101/sys/ship/weaps/docs/mcm.htm.

Freedberg Jr., Sydney J. 2015. “Sowing the Sea with Fire: The Threat of Sea Mines.” Breaking Defense. March 30, 2015. https://breakingdefense.com/2015/03/sowing-the-sea-with-fire-how-russia-china-iran-lay-mines-and-how-to-stop-them/.

Galante, James, Preston Jones, Reid Richardson, and Brian Weber. 2013. *Minecounter Measures Vessel (MCMV).* Report No. NSWCCD-80-2013 West Bethesda, MD: Naval Surface Warfare Center, Carderock Division.

Gaspar, Henrique M., Adam M. Ross, Donna H. Rhodes, Stein Ove Erikstad. 2012. “Handling Complexity Aspects in Conceptual Ship Design.” In *International Maritime Design Conference* (Pre-print version). http://seari.mit.edu/documents/preprints/GASPAR_IMDC12.pdf.

GlobalData Plc. n.d. “Avenger Class Mine Countermeasures Vessels.” Accessed April 9, 2020. https://www.naval-technology.com/projects/avenger-mine-countermeasures-ship/.

———. n.d. “Littoral Combat Ship.” Accessed March 14, 2020. https://www.naval-technology.com/projects/littoral/.

Hall, Nancy. 2015. “Motion of Free Falling Object.” NASA. May 5, 2015. https://www.grc.nasa.gov/WWW/K-12/airplane/mofall.html.

Hart, Laura. 2015. “Introduction to Model-Based System Engineering (MBSE) and SysML.” Paper presented at the Delaware Valley INCOSE Chapter Meeting, Ramblewood Country Club, NJ, USA, July 30, 2015. https://www.incose.org/docs/default-source/delaware-valley/mbse-overview-incose-30-july-2015.pdf.

Joint Chiefs of Staff. 2018. *Barriers, Obstacles, and Mine Warfare for Joint Operations*. JP 3-15. Washington, DC: Joint Chiefs of Staff. https://www.jcs.mil/Portals/36/Documents/Doctrine/pubs/jp3_15pa.pdf?ver=2018-03-14-173117-737.

Kassel, Ben, Seth Cooper, and Adrian Mackenna. 2010. *Rebuilding the NAVSEA Early Stage Ship Design Environment*. West Bethesda, MD: Naval Surface Warfare Center, Carderock Division. https://apps.dtic.mil/dtic/tr/fulltext/u2/a522824.pdf.

Lenzi, Allison F. 2020. “Operational Analysis and Early-stage Design for Next Generation MCM through Digital Engineering.” Master’s thesis, Naval Postgraduate School.

Lockheed Martin. n.d. “Littoral Combat Ship (LCS).” Accessed February 19, 2020. https://www.lockheedmartin.com/en-us/products/littoral-combat-ship-lcs.html.

Makiharju, Simo, Keary Lay, Ryo Yakushiji, Marc Perlin, and Steven Ceccio. 2008. “Partial Cavity Drag Reduction.” APS Physics. https://www.aps.org/units/dfd/pressroom/papers/ships.cfm.

Marolda, Edward J. 2015. “Mine Warfare.” Naval History and Heritage Command. April 9, 2015. https://www.history.navy.mil/research/library/online-reading-room/title-list-alphabetically/m/mine-warfare.html.

McKesson, Chris B. 2006. “A Parametric Method for Characterizing the Design Space of High Speed Cargo Ships.” In *Proceedings of the International Conference High Speed Craft – ACV’s, WIG’s & Hydrofoils*. Report No. P2006-10. London, UK: Royal Institute of Naval Architects. http://resolver.tudelft.nl/uuid:51f7df49-c387-478b-97f3-5aa99aa40ff3.

———. 2011. “The Use of Transport Factor as a Very Simple Model for Ship Design Exploration.” Paper presented at the 11th International Conference on Fast Sea Transportation FAST 2011, Honolulu, Hawaii, USA, September 2011. https://www.academia.edu/20799161/The_Use_of_Transport_Factor_as_a_Very_Simple_Model_for_Ship_Design_Exploration.

———. 2010. “The Utility of Very Simple Models for Very Complex Systems.” In *Proceedings of the 2010 Conference on Grand Challenges in Modeling & Simulation*. 23–29. https://www.researchgate.net/publication/262164291_The_utility_of_very_simple_models_for_very_complex_systems.

Moore, Richard C., Albert W. Horsmon Jr., and Scott B. Clapham. 1996. *Standards Database Maintenance*. Report No. NSRP0456. Ann Arbor: Marine Systems Division, The University of Michigan. https://apps.dtic.mil/dtic/tr/fulltext/u2/a455524.pdf.

Morien, Steven B. 1999. “The Operational Effects of Mine Warfare.” Naval War College. https://apps.dtic.mil/sti/pdfs/ADA363227.pdf.

National Research Council. 2000. *Oceanography and Mine Warfare*. Washington, DC: The National Academies Press. https://www.nap.edu/read/9773/chapter/1#ii.

NAVSEA. n.d. “Naval Sea Systems Command.” Accessed January 10, 2020. https://www.navsea.navy.mil/Who-We-Are/CMDR-Intent/.

Pisani, Christopher R. 2013. “Linking Combat Systems Capabilities and Ship Design through Modeling and Computer Simulation.” Master’s thesis, Naval Postgraduate School. https://calhoun.nps.edu/handle/10945/37695

Program Executive Office Littoral and Mine Warfare. 2009. “21st Century U.S. Navy Mine Warfare—Ensuring Global Access and Commerce.” https://www.gryphonlc.com/images/Mine_Warfare_Primer_2009.pdf.

Ramos, Ana Luísa, José Vasconcelos Ferreira, and Jaume Barceló. 2012. “Model-Based Systems Engineering: An Emerging Approach for Modern Systems.” *IEEE Transactions on Systems, Man, and Cybernetics - Part C: Applications and Reviews,* 42, no.1 (January): 101–111. https://www.semanticscholar.org/paper/Model-Based-Systems-Engineering%3A-An-Emerging-for-Ramos-Ferreira/accfea79696eac40bb01de29e8564d21143afedf

Tran, Hoang N. 2014. “A Preliminary Ship Design Model for Cargo Throughput Optimization.” Master’s thesis, Naval postgraduate School. https://calhoun.nps.edu/handle/10945/42745

Truver, Scott C. 2008. “Mines and Underwater IEDs in U.S. Ports and Waterways.” *Naval War College Review* 61, no. 1 (Winter): 105–127. https://pdfs.semanticscholar.org/7b8f/ad1c3ea6973ea6f18b7a909f4c8cd703b317.pdf.

———. 2012. “Taking Mines Seriously: Mine Warfare in China’s Near Seas.” *Naval War College Review* 65, no.2 (Spring): 30–66. https://digital-commons.usnwc.edu/cgi/viewcontent.cgi?article=1429&context=nwc-review.

U.S. House of Representatives Committee on Appropriations. 2010. *Department of Defense Appropriations for 2010.* Washington, DC: U.S. Government Printing Office.

U.S. Navy. 2016. “Littoral Combat Ships – Mine Countermeasures Mission Package.” https://www.navy.mil/Resources/Fact-Files/Display-FactFiles/Article/2167535/littoral-combat-ships-mine-countermeasures-mission-package/.

———. n.d. “Littoral Combat Ship Class – LCS.” Accessed June 29, 2020. https://www.public.navy.mil/surfor/pages/LittoralCombatShips.aspx.

———. n.d. “Mine Countermeasures Ships (MCM) Avenger Class.” Accessed February 7, 2020. https://www.public.navy.mil/surfor/pages/MineCountermeasuresShips.aspx.

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