A Practical Application of Concept Selection Methods for High-Speed Marine Vehicle Design

by

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Submitted to the Engineering Systems Division
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS DESIGN AND MANAGEMENT

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2008

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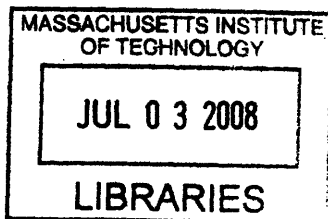
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ABSTRACT

Naval ship design and construction has been in existence for thousands of years. Over that time, many tools have been developed to aid naval architects in the quest for an optimal design, whether fast and sleek like a racing boat or big and square like an oil tanker. In any case, the basic naval architecture design principles are the same.

The following thesis discusses the use of systems engineering principles, including the Pugh concept selection tool and design spiral methodology. Additionally, Chapter 3 provides an example of those principles and methods as they are applied to the hull design for a high-speed naval vehicle. The combination of system engineering principles and methods provided a rapid convergence to a feasible hull design that exemplified the methods taught in the Systems Design and Management program.

Furthermore, recommendations are made for the future of naval vessel design through the use of genetic algorithms for an accurate representation of the value of "real options" as they may apply to marine vessel design.

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ACKNOWLEDGEMENTS

The past three years at MIT have been an unforgettable experience. The education provided by such an institution is sure to lead me down the path to success. I would like to thank the many people who have guided me along the way:

- Jack Grace for his invaluable leadership, unparalleled clarity of thought, and willingness to advise at any moment.
- Pat Hale for providing the necessary guidance, knowledge, and expertise needed to complete this work. His guidance was instrumental in allowing me and my Navy Colleagues to join the SDM program and for that I will always be grateful.
- Professor Pat Keenan, Captain, USN, for all of his mentorship and guidance both in matters of the military, diving and leadership, as well as academic.
- The entire MIT staff and faculty for an amazing educational experience and the United States Merchant Marine Academy for preparing me to take on this challenge.
- My friends and Navy co-workers for helping me make it through MIT. In particular, my co-workers at The Thirsty Ear Pub and Muddy Charles Pub who kept me sane during the last year.

Most importantly, I would like to thank my family for always believing in me and giving me the courage to try each and every day. You are my inspiration and my motivation.

I dedicate this work to my Mom, Dad, Sister, Grandparents, and to the Disabled Veterans who have shown me that you can accomplish anything no matter how great the challenge.

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INTRODUCTION

1.1 Introduction

Since the early Phoenicians, Egyptians, and Norwegians more than two millennia ago, floating vessels have been an integral part of the world economy. During that time, maritime commerce has spanned civilizations, built commercial trade, bridged waters across cultures, and, in many cases, delivered warriors to their field of battle. Naval architecture is the common bond between each of these examples. The systematic combination of design methodologies accelerates the discovery of efficient designs.

The Systems Design and Management (SDM) curriculum provides students with numerous tools for developing systems, designing products, and managing projects; tools that are distributed in class and developed for further understanding. However, many of these tools are not fully utilized until employed either through exercise or practice; most do not reach their full potential until used in conjunction with other methods.

1.2 Motivation

The Secretary of the Defense, Secretary of the Navy, and Chief of Naval Operations have proposed a 313 ship Navy to complete the mission of the United States and project power to shores around the globe [2]. Today, comprised of 276 ships, the U.S. Navy must begin to increase design efforts and reduce ship production times to

avoid the detrimental effect of an aging fleet of warships and submarines to meet the need for a 313 ship fleet. The recent LPD-17, DDG-1000 program, and Virginia Class submarines are just the beginning of the production curve leading the charge to fill the generational gap as the "Regan era" Navy is retired.

The DDG-1000 multi-mission destroyer program, conceived in 1994, and the Littoral Combat Ship (LCS) which is now in production, have been riddled with problems. The LCS, originally priced at $220 million, has grown to $400 million per ship and the DDG-1000 program, thought to reach production in 2005 has been delayed until 2008 with delivery scheduled for 2011 [3, 4]. DDG-1000 has been in the design phase for over thirteen years and was only recently awarded to two shipyards; an example of pork barrel politics costing $300 million per ship to be incurred by the government and taxpayers [3]. The DDG-1000's technological advances include systems which allow the expansion of the Navy's battle space capability by 400%, a hull form and superstructure with the radar cross-section of a fishing boat, and the quiet operating capability of the Los Angeles class submarines. While the technological advances are vast, this example of a long and drawn-out design process requires the need to return to fundamental design procedures.

1.3 Thesis Overview

The following work is a compilation of design principles applied to the design of a high-speed hull design for the MK-V Special Operations Craft replacement. It is the hypothesis of this thesis that a combination of these tools can provide insights into design options and provide more rapid convergence to a feasible hull design solution. The design process implemented exemplifies the methods introduced and practiced during the Systems Design and Management course of study.

2

DESIGN PROCESS & METHODOLOGY

"If I had asked my customers what they wanted, they'd have said a faster horse."

   - Henry Ford (1863-1947)

2.1 Introduction

As Henry Ford implied and demonstrated with the automobile, the customer does not always know the best solution, but an enlightened engineer's interpretation of their needs can lead to superior solutions and vast advances in technology to benefit the common man.

Ship design is both art and engineering. It encompasses architecture and mechanics in order to provide functional designs to the consumer. In the early design phases, the systems engineer's most important objective is not to eliminate ideas or concepts without justification [20]. However, precedence may be used to eliminate previously evaluated concepts that are incompatible with the overall objective or to narrow concept requirements thereby reducing time and effort in the design process. Additionally, as more information is discovered, customer needs should be interpreted and refined using unbiased methods at each selection round in order to meet the specific objectives of the design; thus, avoiding concepts that lead to an inferior product. Those methods are described in this chapter.

The initial discussion focuses on the Design Phases as they occur in the acquisition process. The second discussion explores the methods used to make decisions within each phase.

2.2 Systems Engineering Principles

"Systems engineering" broadly encompasses four over-arching principals that are intended to identify requirements and interactions between system components. In short, these principals provide an architecture framework that is used to focus the design process towards a final product that is capable of satisfying the requirements of the customer and is producible. The engineer's mental process encompassing the entire system from design conception to end has been termed systems thinking. Ultimately, systems engineering theory contributes to the design of a robust product proven over years of service. The main principals of systems engineering are:

- Identify a need / opportunity.
- Identify the stakeholders.
- Gather requirements.
- Needs Analysis: Establish the problem space & limitations.

2.2.1 Identify Need and Opportunity

Identifying the need for a new technology, system, or weapon platform is the first step in systems engineering [5, 9]. Without establishing a need or attempting to satisfy a customer's desire, there is no potential for development of a successful product. The opportunity for a new product may be established through interpretation of the customer's needs, which include recognition of new technologies, competition, or outdated equipment [5]. New technologies may present themselves as generators of

technology gaps where one product surpasses others leaving a void in the market. Advancing technology not only affects the nature of the product, but can directly change the way products are engineered and incorporated into larger systems.

Competition can provide a great source of development incentive as well as design options including new technology. In the military context, competition may mean the introduction of a new enemy or recognition of an enemy's advancement whether technological or tactical. In either case, this advancement can be combated with new tactics, but, as the enemy closes the superiority gap that the U.S. maintains, eventually different material solutions will be needed.

Outdated equipment is perhaps the most recognizable characteristic that results in a definite need for the introduction of new equipment, tools, and technologies. The need to update systems can easily be identified by increasing maintenance costs, increased down time, and reduced productivity or on station time. This is the primary reason for the MK-V Special Operations Craft Replacement example in Chapter 3.

2.2.2 Identify the Stakeholders

Once a need has been identified, the parties with direct interest in the project must be identified [5, 9]. Most will be easily identified, while some may be manifested on paper only for guidance. Depending on the stakeholders role, they should have a concept of what will make their job easier, more effective, or increase efficiency; their needs. The major stakeholders are identified according to their level of responsibility and usefulness to the project. For the example in Chapter 3, the stakeholders are as follows:

- Naval Executive leadership – Secretary of the Navy and Chief of Naval Operations.
- Legislators who provide purchasing authority.
- Program offices responsible for designs and life-cycle management.

- Command Forces responsible for deploying systems.

- Operators of the product.

- Maintainers of the product and sub-systems.

- Bureau of ship constructions standards: i.e. American Bureau of Shipping.

The Naval executive leadership has provided their guidance reflecting the need for a 313 ship Navy in order to fulfill the United State's mission. Legislators provide the purchasing authority for programs, which, in turn, is executed by the program offices who manage the project from design conception and construction to disposal. The maintainers and operators must have a stake in the design process in order to prevent mistakes that make the product unusable.

A very prevalent example of the stakeholder's lack of influence is provided in Chapter 3, which addresses the handling characteristics of the MK-V. While the MK-V has provided nearly 15 years of service, nearly 100% of the operators have been injured due to ride conditions after 9 years of service. This illustrates a lack of concern for the vessel's occupants and design functionality [11].

Similarly, the government's stated objectives for the Littoral Combat Ship (LCS) were to build a ship that could travel at speeds better than 40 knots and could be outfitted with different weapons and surveillance systems including a removable package of mine-sweeping equipment interchangeable with a package of special-operations gear used by a SEAL team [30]. However, the U.S. Navy and prime contractors lost focus early in the process when lawmakers sought to rapidly build inexpensive ships instead of concentrating on the war-fighting requirements.

2.2.3 Gathering requirements

Gathering stakeholder's requirements provides the opportunity to set expectations early in the process, but depends on the system engineer's interpretation of the customer's needs [5, 9]. A mutual understanding between the customer and the engineer is paramount in order to alleviate future complications later in the life-cycle of the design and operations of the product. Requirements can be simply defined with a range of values or as specific as an exact number such as the number of people required to operate the final product. In fact, requirements can be iteratively refined throughout the design process as more information becomes available or realistic expectations are adjusted for timely solutions. During the requirement gathering process, it is wise to analyze a number of options in order to provide differing levels of complexity, price, and effectiveness [20].

2.2.4 Needs Analysis: Establish Problem Space & Limitations

The final step in the requirements definition is analyzing the desired needs of the stakeholders and establishing the problem space [5, 9]. This step establishes the relative importance of the needs according to contribution to the overall objective. Additionally, in the context of interpreting needs, reflection on the design requirements can provide validation for the high level requirements, define the limiting characteristics for feasible solutions, and provide an outlet for clarification prior to entering the design phases. Limiting factors may manifest in dimensional constraints or compatibility with existing hardware, software, or system infrastructure.

The ultimate goal of the needs analysis is to create a set of formal and quantitative functional requirements. In military or government contracting this is the Initial Capabilities Document (ICD).

2.3 Design Phases

Ship designs prove to be complex by themselves, but added complexities may be introduced through the externalities of the process. External factors in government and acquisition processes appear in many forms: budget constraints, bureaucratic party lines, congressional districts, acquisition process, and manufacturing capabilities that attempt to push design considerations in one direction or another. After 200 or more years of experience, organizational culture may be one of the strongest influences in defining the boundary between wants and needs. In some cases organizational culture could be beneficial provided that decisions are made rationally and with unbiased precedence gained from past experience. Conversely, experience can be detrimental in early concept design stages of by stifling creativity and limiting technologically advanced solutions.

The acquisition process has been documented throughout the government and is well known by lawmakers, defense agencies, and contractors. Figure 1, is a simplified, high-level graphical representation of a very complex and detailed acquisition process. This process begins with the concept phase and ends with the operation and disposal of the final product; far beyond the discussion in this paper. Funding milestones A, B, and C correlate to acquisition reviews during the design process and production phases. If accepted at each milestone, additional funding from the approval authority will be granted and the design will move into the next phase of design or construction. For the purpose of this thesis, discussion will be focused in the beginning phases of the acquisition process prior to entering full rate production shown in green (Figure 1).
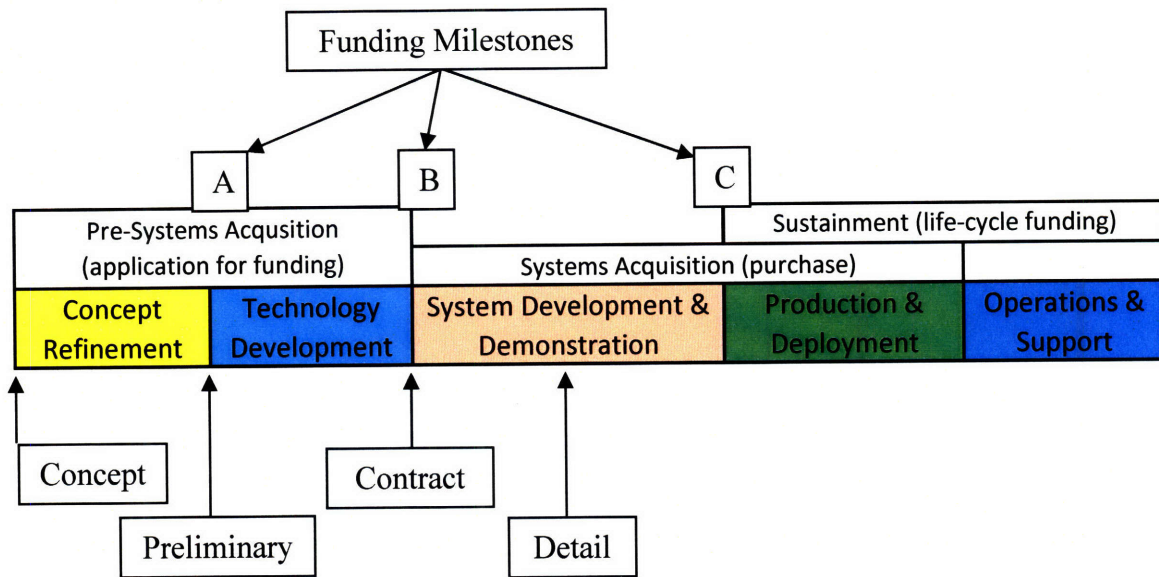
Figure 1: Acquisition Process & Design Phases

2.3.1 Concept Design Phase

The first phase of design, also known as the concept phase, is the beginning of the design process where customer requirements are defined [20, 21, 22]. At this point in the process, the concept is established by identifying a gap between the market (battlefield need) and the current operational doctrine or an available material solution. The initial concept phase produces a broad, high-level solution space and suggests total system combinations which can be broken down into individual functions or sub-systems in later, more detailed design phases. During the initial concept phase, high-level requirements may limit system solutions with broad requirements like engine fuel type for infrastructure compatibility or hull dimensions for size limitations [20]. For example, a primary concept requirement could limit a vessel's beam (< 110 feet) for transit through the Panama Canal or a length less than 85 feet in order to meet the transportability requirements of a C-17 Globemaster cargo aircraft. Ultimately, if the design were not able to meet specific requirements, it would be discarded.

The concept design phase ends with the production of an Initial Capabilities Document (ICD), which designates the minimum (threshold) and objective (goal) requirements to produce a design capable of successfully completing the intended mission as defined by the customer. In ship design, capabilities may include number of personnel, range, speed, handling characteristics dependent on sea conditions, and personnel habitability requirements among other system specific requirements.

2.3.2 **Preliminary Design Phase**

The preliminary design phase establishes relationships between the systems, sub-systems, and system components to ensure functional operation [20, 21, 22]. Ensuring proper interface among selected technologies ensures the feasibility of the overall design. In the most basic form, this phase provides a trade-off analysis from one system to the next or challenges the reliability of one system compared to another. Issues concerning the technological risk of a system may also be addressed and mitigated by integration with other components within the concept. Throughout the selection process there is an opportunity at each phase to iterate design interactions in order to find the components that provide maximum feasibility in the construction and operation of the final product.

One such technology that created additional risk in the production of a vessel due to selection of immature technology is the CVN-78 electromagnetic aircraft launching system (EMALS). EMALS uses advanced electromagnetic technology to launch aircraft from the aircraft carrier, creating the need for additional electrical power supplied by the ship's power systems to charge high power capacitors that, on discharge, will produce the force required to launch a 70,000 pound aircraft. If development is not successful, in order to mitigate this risk, a traditional steam catapult system may be used.

Essentially, the preliminary design phase is used for progressive and continuous design refinement [21]. Graphically, the preliminary design stage is the outer ring of the design spiral shown in Figure 3.

2.3.3 Contract Design Phase

Over 30 years ago, the U.S. Navy designed almost every aspect of a new ship in-house. However, because ships have grown larger, technologies have increased, and the demand for faster design and production rates are more demanding, the Navy has contracted much of the design work out to government contractors with expertise and resources available to design, test, and build the next generation ships [27]. For example, the U.S. Navy has spent billions of dollars to have government contractors design and test the DDG-1000 hull design and ship systems; Northrop Grumman and General Dynamics are two such contractors working on this project.

The end of the contract design stage indicates a transition point at which designs move from the government to contractors. This transition is accomplished with a request for proposal (RFP), which provides general requirements and system specifications. An RFP provides system specifications rather than system components in order to encourage shipbuilders to generate innovative designs tailored to their particular manufacturing capabilities and technological specialties. Additionally, the contract phase lays out the basic characteristics of the ship such as compartments, mission critical areas, weapons systems, and, in many cases, equipment in the government's inventory that will be furnished by the Navy, Government Furnished Equipment (GFE). GFE is primarily used as a tool to defer financial risk from the contractor while the government assumes cost and provides system commonality between weapon platforms as well as compatibility across generations.

2.3.4 Detailed Design Phase

The detailed design phase is the fourth and final design in the acquisition process [20, 21, 22]. Final ship designs produced by the contractors are detailed drawings accompanied by equipment specifications and a build plan that outlines the build process and assembly of the ship during construction. After successful completion of Milestone C, the Detailed Design Phase, allows the program to enter Low Rate, Initial Production (LRIP) and establishes funding for ship construction [28].

After the lead ship is completed and actual performance is assessed, further modifications may be made during the build process prior to commencing full rate production. At this point, the focus of design modifications is to simplify the build process and improve functionality of the system. A second detailed design will be submitted for review prior to full rate production in order to provide modifications and remove any issues that would otherwise be carried into the follow-on ship production.

According to the *New York Times*, the downfall of LCS program occurred during the detailed design phase with the government's "policy of letting contractors take the lead in managing programs," which "has coincided with an acute shortage of government engineers trained to oversee these increasingly complex enterprises" [30]. In short, the number of government engineers qualified to provide contractor oversight is not commensurate with the complexity of shipbuilding.

2.3.5 Program Risk

In the area of military acquisitions, program risk addresses whether or not the program, i.e. government office, will continue to receive funding from the approving authority after demonstrating the future value. The term program risk is not related to the technological risk previously mentioned. Success is rewarded with additional funding, which provides the means for additional design effort. During each phase of the design

process, the number of man hours available for the project increases until production work begins and design work ends. Figure 2 illustrates the associated program risk and level of effort versus the design stage [5]. The concept phase requires very little man power to develop the initial capabilities document; conversely, the detailed design requires significant effort to ensure the ship blueprints are accurate and physical construction challenges have been addressed from the ship building facility's perspective. At the point of awarding a contract during the design phase, there is relatively little risk of program cancelation due to political interest from congressional districts and the unlikelihood of discarding advances made during the previous phases. Once the contract is awarded to a prime contractor, the design phase continues with increasing detail until the integration and evaluation stage; this would coincide with low rate initial production.
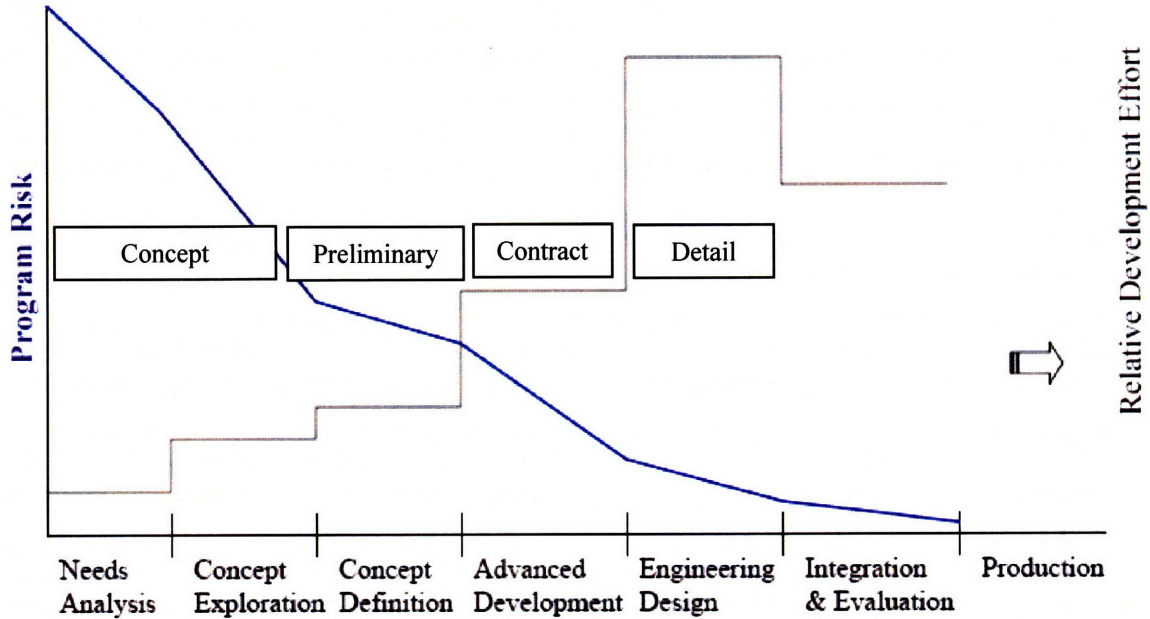
Figure 2: Program risk and effort versus design stages [5].

2.4 Design Spiral

The design spiral below is the classical representation of a naval architect's approach from a problem statement to an initial concept design where the refining iterations begin eventually leading to convergence at the final detailed design [20, 21, 22]. Each spoke on the spiral provides a checkpoint for the design process as the concept moves from the original statement towards a final design at the center with greater detail; Figure 3. Fundamentally, the spiral is an algorithm that allows options to be explored at each node while exploring the relationship between systems; iterations are performed as necessary until a feasible design is achieved.
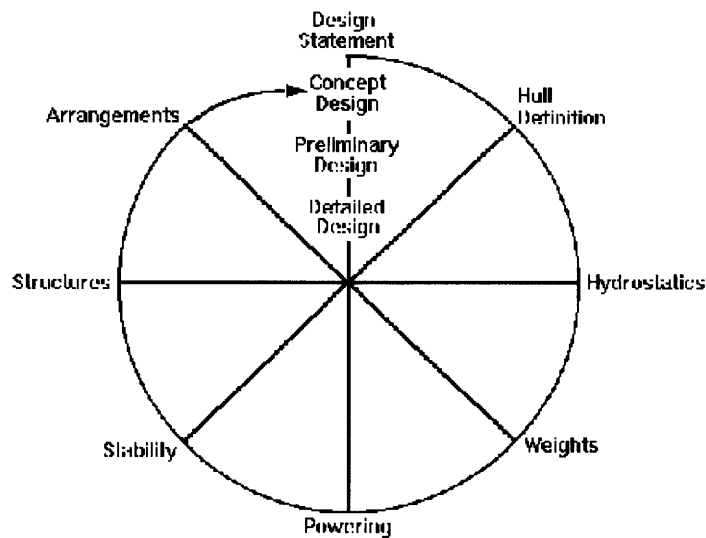
Figure 3: Design Spiral

The design statement at the starting point is the beginning of the systems approach. At this point, the mission needs and stakeholder requirements understood at the most basic level. Each stage beyond this level will continually narrow the requirements to a singular solution or group of solutions that best fit the mission of the vessel. Depending on that mission, whether a cargo carrying merchant ship or high-speed warship, classification societies (American Bureau of Shipping, Lloyds, etc.)

provide published standards pertaining to sea keeping, structural integrity, crew and environmental safety factors that can be consulted throughout the design process. Typically, U.S. Navy standards meet or exceed societal standards due to war fighting and damage resistance necessities factored into vessel designs.

It is important to note that other design philosophies may provide much more resolution. However, it must also be understood that the spiral is not a regimented process; rather a visual representation of the iteration that occurs during design from an established capability gap or need to final design. Throughout the iterations, designers will quickly realize which factors dominate the design and which are highly correlated to other factors in the design. For example, reducing crew size by five people will affect the number of berths required, subsequently affecting the size of the vessel, propulsion required, acquisition, operation (fuel and personnel), and maintenance cost [20, 21]. In some cases, such as a small craft with high-speed requirements and volume limitations, several spokes may be a near simultaneous assault on the designer's abilities as Figure 4 illustrates.
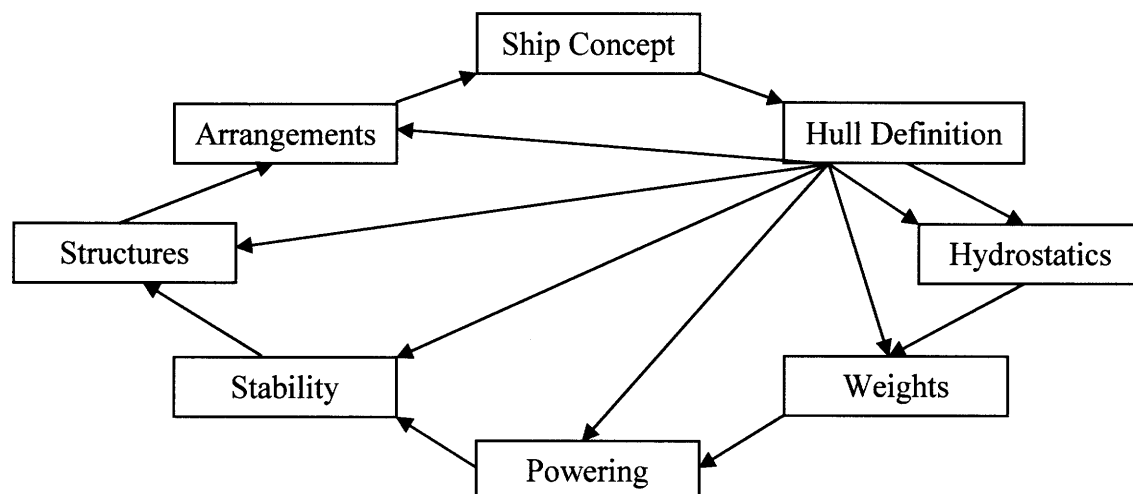
Figure 4: Simultaneous design spiral interactions.

Because of the small size and high-speed requirement for the project referenced in Chapter 3, the bulk of design time was concentrated at the hull definition, hydrostatics, and powering spokes.

2.5 Pugh Concept Selection

During each stage of the design process the engineer must addressed the tradeoffs in order to find the optimal solution. The Pugh concept generation and selection method enhances the engineer's ability to address issues as more information becomes available and the horizons of knowledge are expanded. Using the Pugh design method provides a framework to rank the alternatives from best to worst and provides insight to compatibility of components with other system options throughout the design [26]. Figure 5 illustrates the process showing the basic funnel concept where ideas are eliminated (concept convergence – CC) and, through research and brainstorming, more concepts are generated (CG). This method increases the number of possibilities that the designers can explore, while decreasing the initial number of variants and combinations of complex alternatives.

Front-end design work
↓
PDS
↓
Concept generation

Initial number of
concepts based
on PDS

Apply controlled
convergence (CC) →

Initial number reduced

Apply concept
generation (CG) →

New ones added

CC →

CG →

Further reduction
(FR)
Further addition
(FA)

CC →

CG →

FR
FA

CC →
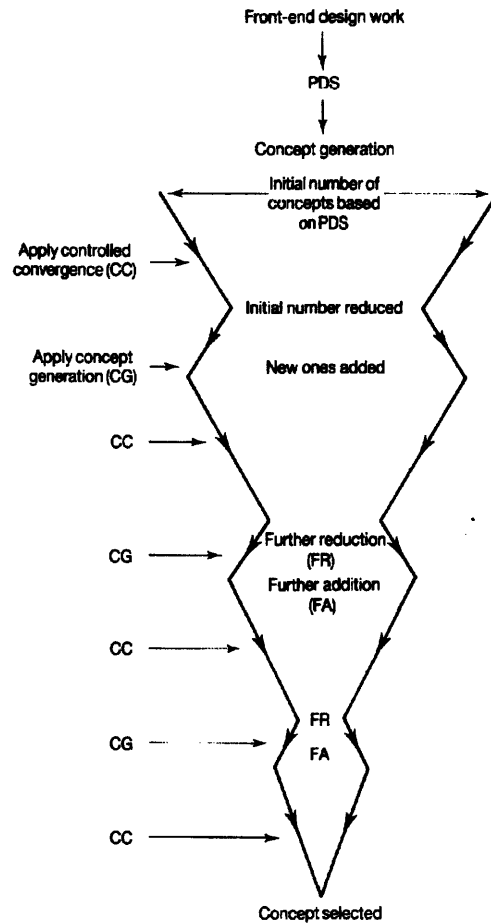
Concept selected

Figure 5: Pugh Concept Selection Process [26]

The use of this process is demonstrated in the hull alternatives section of the small vessel design example provided in Chapter 3. Initially, multiple hull types were considered and progressively eliminated due to size requirements dictated by mission requirements. Once the initial convergence was completed, analysis continued with different hull characteristics and dimensions versus a baseline design, eventually leading to an asymmetric catamaran hull design with specific dimensions and speed capabilities. Dimensional analysis can then be employed using the Design Of Experiments (DOE) to optimize the dimensions of the vessel.

2.6 Design of Experiments

A structured approach to the Design Of Experiments (DOE) combines the knowledge of process operators, engineers, and statisticians. Taguchi established a hierarchical ranking of the most important factors from input from each of the stakeholders and their needs and weighted them accordingly [23]. Factors for the experiments are given acceptable ranges according to parameters determined from the objective requirements, such as the width or overall length of a vessel. Additionally, noise factors should be incorporated into the experiment and assessed for significance. Once all factors have been identified, orthogonal arrays may be constructed to develop the experimental test runs. While every combination can be tested, a realistic sample size may be used to eliminate redundant results and reduce run time of the experiment. Experiment results aid in determining combinations of the main effects, defined interactions, and the significance of the measured response.

In the hullform dimensional analysis example in Section 3.4, a software program, JPM 5.1, which evaluates variables relative to their importance, was used. JMP 5.1 provided an L27 matrix (9x3) with the variable parameters extracted from the requirements. Through investigation of the resulting trends during the initial round of experiments, the matrix was subsequently reduced to an L9 matrix. Analysis of all combinations in an L27 matrix was determined to be unnecessary and redundant once trends were discovered. The trend shows a strong correlation to known naval architecture principles; displacement is the dominant characteristic in vessel designs. Further discussion will occur with the data presented in Section 3.4.

2.7 Summary

System Engineering encompasses a number of principles that have been described throughout this chapter. By examining each principle and employing the techniques described, the engineer is capable of designing robust systems capable of exceeding stakeholder's expectations. While the processes have been described individually, combinations of the design spiral, Pugh concept selection method, and design of experiments should lead to more efficient design processes and product; an example is provided in Chapter 3.

3

DESIGN PRINCIPLES APPLIED

"Enlightened trial and error succeeds over the will of the genius."

- IDEO, Inc. Executive from an ABC News special.

3.1 Introduction

The following example was extracted from a U.S. Navy design project completed by the author, LT Colin Dunlop, and LT Benjamin Hawbaker, active duty officers in the U.S. Navy. While assistance was provided by the group for data entry of multiple hull parameter combinations for hydrostatic calculations; the hull selection theory, Design Of Experiments, and analysis of results are entirely the author's own.

The hull analysis of this high-speed craft lends itself to an example of design concept selection and refinement methodologies discussed in the previous chapter. Specifically, the Pugh concept generation and selection process was used to determine the best hullform and eventually the most efficient catamaran design. The initial capabilities document was adapted from the established needs of the stakeholders, the capabilities of the current U.S. Navy high-speed special operations craft, and the strategic guidance published by the Chief of Naval Operations. Allotments have been made for technology increases, improved propulsion systems for greater speed, and additional mission objectives.

3.2 Systems Engineering Concept Definition

3.2.1 Identify Need and Opportunity

Recent events and conflicts around the world have forced the United States military to focus on a new breed of enemy. This enemy is not willing to be seen on the open ocean in large ships like the World War II era enemy, rather hides in the smallest, most remote areas and waits for an opportune time to attack. This enemy threatens our way of life and that of the people in the vicinity of the attack. The United States must change the concept of operations by employing smaller, more clandestine vessels capable of operations without the reliance on large combat ships or support networks.

The MK-V Special Operations Craft (SOC) was originally developed in the early 1990's for rapid and clandestine SEAL delivery in the littoral or riverine areas of operation, an operating area that has become more prevalent on today's battle fields. The current MK-V design began service in 1995 with the delivery of the first two boats. The MK-V's intended service life consisted of 1,000 hours of operation each year for fifteen years leading to the need for a replacement by 2010. At approximately two years away from that deadline, naval architects are exploring the possibility of a more efficient hull form, increased mission capabilities, and performance improvements over the current design.

3.2.2 Identify Stakeholders

The MK-V Special Operations Craft is designed to transport U.S. Navy S.E.A.L.s to their area of operation and has a very specific role in the special operations community. U.S. Special Operations Command (USSOCOM) in Tampa, Florida provides the leadership and tasking direction for this highly specialized community. USSOCOM is the final deciding entity for the procurement of special operations

equipment and materials within each military branch. Additionally, USSOCOM is tasked with execution of the Chief of Naval Operation's strategic guidance as it pertains to the special forces community. Engineering technical advice is provided by the Naval Sea Systems Command (NAVSEA) in Washington, D.C. The special boat squadrons are collocated with the SEAL commands in Coronado, California, and Little Creek, Virginia. Special Boat Squadrons provide the crew to operate and maintain the boats on a daily basis and on each mission. The Navy SEALs join the boat squads for training and actual missions. Further into the acquisition process, legislative interests may be introduced via shipyards capable of providing the vessel described by the requirements definition within a particular congressional district. Ultimately, each stakeholder has a voice in the design process to ensure their needs are understood and elimination of any early in the process may compound the difficulties later.

Stakeholders

- U.S. Navy leadership strategic guidance via U.S. Special Operations Command.
- Legislators.
- Naval Sea Systems Command.
- U.S. Special Operations Command.
- Special Boat Squadrons – Special Warfare Combat Crewmen (operators and maintainers).
- U.S. Navy SEALs.
- Shipyards capable of vessel production.

3.2.3 Gathering Requirements

Gathering the requirements for the MK-V Replacement design was, in some cases, the most difficult part of the process. Each stakeholder provides different insights particular to their interests and assesses differing levels of importance to factors that may ultimately become system level requirements.

Considering the past performance of the MK-V, there are a particular set of issues that must be solved for a replacement design to be successful. First, the Small Boat Squadrons operating the MK-V have addressed the issue of hydrodynamic stability and ride comfort. The current vessel is subject to slamming and porpoising in sea states 2 and 3 and proves to be an unpleasant and sometimes hazardous ride for the crew and passengers. Through investigation, the vessel is required to achieve speeds of 35 knots in sea state 3 and 50 knots in sea state 2. Sea states are a term used to describe significant wave heights that are expected to be encountered.

Evidence stated in an Office of Naval Research report from 2002, "154 respondents had 722 cumulative years of SBU (Special Boat Unit) exposure, and 100 respondents reported at least one injury. Most of the injuries were strains or sprains of muscles and joints, but fractures and dislocations, arthritis, and chronic pain were also reported. The majority of injuries occur in four locations: neck/shoulders, lower back, knee, and ankle regions" [11, 12]. Further interpretation of this data shows that 100% of the operators have sustained a shock related injury by the 9 year mark in Special Boat Unit service. This evidence provides substantial reason to increase the importance for a replacement vessel hull design that reduces slamming effects.

The second source, an interview dated 4 June 2007, with Captain Evin H. Thompson, USN, Commander Special Warfare Group Four, addressed the fleet of assets available to the Special Operations community [24]. Specifically, Captain Thompson mentions the use of Cyclone Class Coastal Patrol ships, the 25 ft river patrol boats, and

the MK-V Special Operations craft. The Cyclone Class, a 170 foot long ship capable of 35 knots, performs long range missions and provides specific advantages that a MK-V cannot such as remaining on station for long periods of time and missile defense. He specifically addressed the Cyclone's shortfalls as well:

- The draft got too deep – "it couldn't go all the places we wanted it to."

- "Creature comfort was given priority instead of the mission."

Captain Thompson also stated solutions, likes, and desires of the Special Forces Community for the next generation Special Operations Craft, without specifically endorsing the Combat Craft Heavy (CCH), a vessel in early concept stages and similar definition as the boat described in the following sections. The future design solutions and recommendations to the Cyclone's problems were stated as such:

- Eliminate the need for racks (beds-creature comforts) on board.

- Range: can stay on station.

- Missile System – "One thing I think we missed with the Cyclones was not putting a missile system on them."

Captain Thompson's remarks and the ONR report introduce the need for the design of a vessel capable of carrying a missile system and delivering SEALs, while fulfilling the top priorities stated above [12, 24]. While the Chapter 3 provides an example of the hull form design process, the final vessel design introduces shock mitigating characteristics into the hull, deck mountings, and will be constructed of materials capable of absorbing energy produced by wave impact on the hull [13, 14, 31].

Top level hull design factors:

- Sea Keeping.

- o Reduce slamming injuries to crew and SEALs.
    - ▪ Sea State 2 – 50 knots.
    - ▪ Sea State 3 – 35 knots.
- Speed (hull resistance): in excess of 50 knots at Sea State 2 or less.
- C-17 cargo hold maximum dimensions:
    - o 85 ft x 17.5 ft wide x 12.5 ft high.
    - o To include equipment, crew, and supplies.
- Mission.
    - o Shallow draft: less than 3.5 feet.
    - o Payload (gear & personnel): at least 7,500 pounds.

3.2.4 Needs Analysis: Establish Problem Space & Limitations

The high-level limitations for the MK-V Replacement craft have been established through the previous system engineering steps. The following sections limit the discussion to the hull form in order to show a specific example of the design process. In a full scale design project encompassing the entire vessel, additional factors such as a propulsion system, electrical systems, and vessels structure would be included. The completion of those aspects may be reviewed in the paper, "MK-V S.O.C. Replacement design study" [31].

Need: Transportability

The U.S. Navy's strategy and analysis of the operational profile from the SEALs and special boat crews establishes a requirement for a vessel capable of rapid transport to any theater of operations within 48 hours. This implies air transportability by the future of U.S. Air Force airborne logistics; the C-17 Globemaster cargo aircraft. While more

fuel efficient, C-17's has a cargo compartment 50 feet shorter than the C-5 Galaxy which transports the current MK-V.

Need: Shallow draft, long range, and high-speed

Captain Thompson requires the vessel to provide a shallow draft (< 3.5 feet) for littoral operations and as well as a useful range and high-speed, which was determined by previous operational standards to be 500 miles and 50 knots, respectively, while operating in Sea State 2 or less [1, 24]. The operators require speeds in excess of 50 knots for rapid insertion and extraction. SEALs typically carry over 100 pounds of dive gear, weapons, and ammunition and commonly deploy from the vessel in 16 feet long combat rubber raiding craft (CRRC). Each of these requirements factors into the overall weight, which in turn affects the draft and speed. Further iterative refinements are required throughout the design process to determine the optimal combination of weight, speed, payload, and dimensions.

3.3 1st Pugh Concept Generation/Convergence: Hull Analysis

The initial problem space involved a number of hullforms including the traditional monohull, catamaran, trimarans and advanced hullforms. Although they were not likely selections due to design complexity and overall dimensions, the advanced hullforms were evaluated in a pure sense to avoid eliminating any option with personal bias or without justification. Numerical rankings are provided on a scale of 1, 3, and 5 for the Pugh matrix evaluation, 5 being the best.

The baseline criterion was established by comparison to the monohull characteristics. Criteria not directly related to the hull form were not evaluated; such as self defense, which would be measured by evaluating weapons systems installed on the

vessel. Furthermore, later in the design process, additional criteria could be included to address either volumetric or weight margins within the vessel that would allow for future equipment added to expand the vessel's capabilities. Figure 6 through Figure 9 show the range of vehicles initially considered for use in this design project.

Table 1: Hullform Analysis versus Requirement

	Customer Requirements	Monohull	Catamaran	Wave-piercing Cat	Trimaran	Hovercraft	Hydrofoil	SWATH	Surface Effect Ship
Performance	High-Speed (> 35 knots @ Sea State 3)	3	3	5	1	1	1	5	1
	High-Speed (> 50 knots @ Sea State 2)	3	3	5	3	1	3	5	1
	Sea Keeping (< Mk-V)	3	3	5	3	1	1	3	1
	500 Mile Range	-	-	-	-	-	-	-	-
C-17 Compat	Beam (< 17.5 ft)	5	5	1	1	1	3	1	5
	Length (< 85 ft)	5	5	3	3	3	3	3	5
	Height (<12.5 ft)	5	5	1	5	3	1	1	1
Mission	Shallow Draft (<3.5 ft)	3	3	1	3	5	5	1	1
	20 Personnel	-	-	-	-	-	-	-	-
	2 CRRC's	3	3	1	3	3	1	1	3
	7500 lb Payload	3	3	3	3	1	1	3	1
	Self Defense	-	-	-	-	-	-	-	-
	Surface-Air missile sys	-	-	-	-	-	-	-	-
	Reliability/Survivability	-	-	-	-	-	-	-	-
	Total Score	33	33	25	25	19	19	23	19

Based on the vessel size and speed requirements, it was clear that a planing hulls or an advanced hullform, such as a hydrofoils, hovercraft, hydroplane or surface effect ships, would be the only practical solution eliminating all true displacement hulls with a deep draft (> 3.5 feet) such as a monohull destroyer (17 feet draft) or cruise ship type vessel.

The trimaran scored low in both the beam and height categories based on parametric data that shows the precedence for typical trimarans to have square

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Chapter 3: Design Principles Applied   34

dimensions [29]. While trimaran characteristics instill great stability it also prevents airborne transportation due to a typically wide beam compared to most other hull designs.
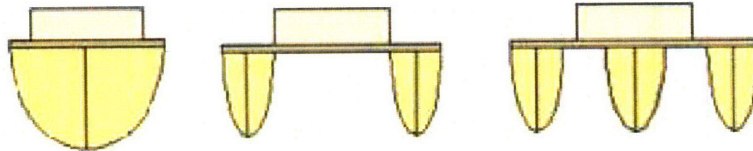
Figure 6: Monohull, Catamaran, & Trimaran

While advanced hull forms have established benefits, they also have limitations that are addressed in the matrix above. Wave-piercing catamarans and Small Waterplane Area Twin-Hull (SWATH) are known to have very good sea keeping characteristics due to a wide beam and submerged hull structure. However, the height from the keel to the top of the superstructure precludes them from airborne transportation. Conversely, the hovercraft (LCAC) and trimarans are primarily used in high-speed operations and do not have large submerged structures.
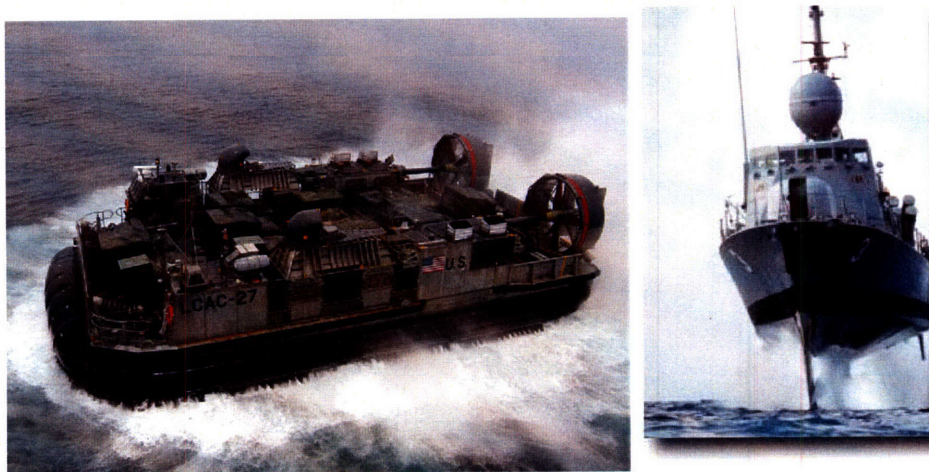
Figure 7: Landing Craft Air Cushion & Hydrofoil

Even though the Landing Craft Air Cushion (LCAC), commonly known as a Hovercraft, has virtually zero draft, it did not meet the design requirements because of the large beam-to-width ratio that is typical of such a vessel similar to trimarans.

Although capable of high speeds, hydrofoil vessels typically have a height that would exceed the maximum allowable cargo height of the C-17 much like the SWATH and wave-piercing catamaran. While removal of the foils would have provided a solution, it was discarded due to the complexity of reattaching the hydrofoils after transport; a time consuming process that would increase the mission risk factor and was deemed unnecessary should a catastrophic failure occur. Additionally, hydrofoils are limited to deep water at slow speeds and will only be able to sustain shallow draft at maximum speed up on the foils as shown in Figure 7.
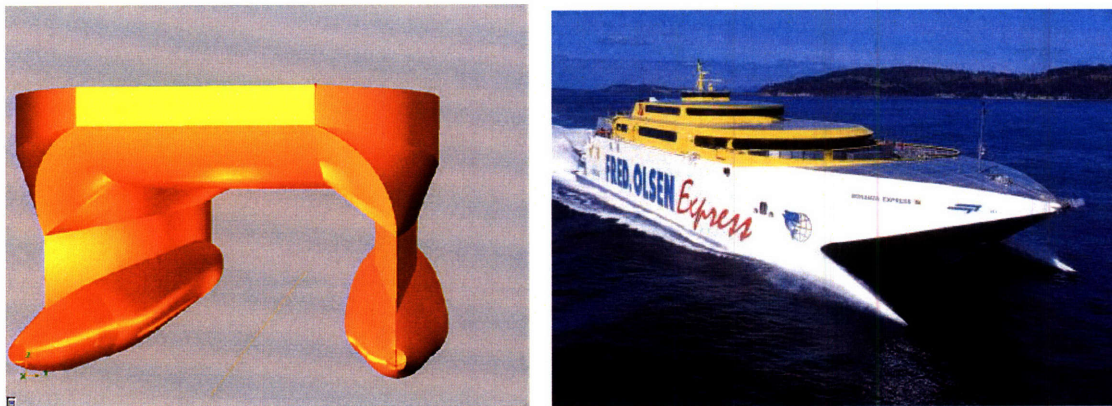
Figure 8: SWATH & Wave-piercing Catamaran

The remaining three vessels, SWATH, Wave-piercing Catamarans and Surface Effect Ship (SES), possess structures below the waterline that are not removable or adjustable. Though the Pugh matrix identifies several reasons to eliminate these designs, the vessels were removed from consideration primarily due to the deep draft characteristics and rigid structures that prevented C-17 compatibility and transportability.

A monohull and catamaran were, therefore, selected as the only logical solutions based on the speed capability and dimensional requirements.
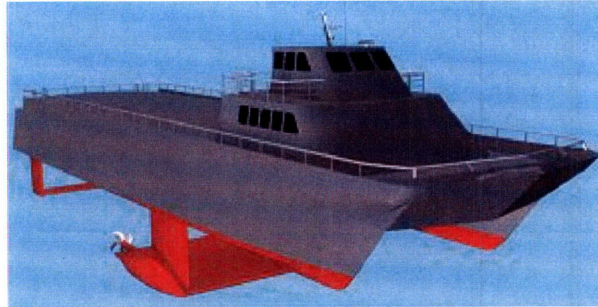
Figure 9: Surface Effect Ship

The advanced hull forms were subsequently discarded without the need for significant study, as they represented an unacceptable level of complexity, risk for the given mission, and transportability limitations. Further analysis continued within the speed regimes in the next section.

Displacement Hull versus Planing Hulls

Systematically eliminating the advanced hullforms from the selection process allowed the team to focus on the comparison of displacement hulls and planing hulls within the monohull and catamaran families. In this case, the comparison was made between a true displacement hull similar to a Navy Frigate or Air Craft Carrier and another ship capable of more than 30 knots.

The High-Speed Displacement ships, while capable of reaching speeds in excess of 50 knots, according to the figure below, are basically true displacement hulls with an extremely large power plant. These vessels are also known as Semi-displacement hulls for their displacement hull characteristics at low speeds and near-planing capability at high speeds. Similar to the true displacement hull, a high-speed displacement hull would induce much higher hydrodynamic resistance and require significantly more power to

achieve 30 knots, still short of the stated objectives. In light of the design spiral, the addition of a large power plant capable of pushing a vessel to those speeds would require an extreme amount of fuel, adding weight and volume to the vessel design. While a quantitative analysis of these effects was by-passed, verification would be accomplished in the contract or detailed design phase iterations.

These conclusions led to establishing the goal of designing a planing hull for the lower power requirement to reach 50 knots and the relative fuel efficiency at higher speeds compared to the fuel consumption of a high-speed displacement vessel at the same speed. Illustration of the speed regimes is shown below in Figure 10.
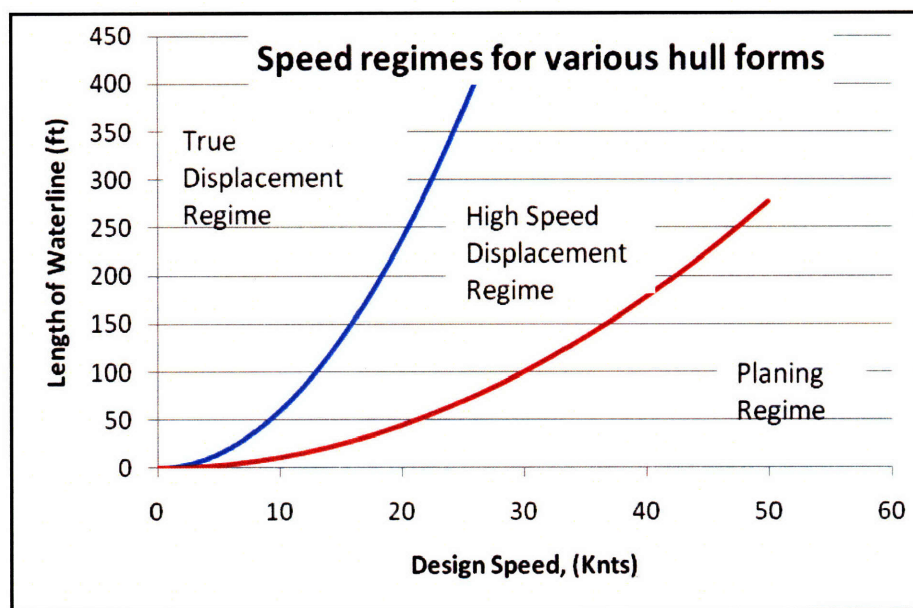

Figure 10: Speed Regimes

Within the planing regime, the number of hulls, monohull or catamaran, represented another area of investigation. Figure 12 in Section 3.4 provides evidence that a monohull may have a slightly lower power requirement than the catamaran; however, the catamaran was chosen for the final design concept due to an inherent stability,

shallow draft, and high-speed capability as identified in the Pugh matrix. Unfortunately, the quantitative merits of a catamaran versus a monohull design were not fully known, leaving the issue open for further study; thus, the monohull is used for comparison throughout the study.

3.4 2nd Pugh Concept Generation: Multi-Hull Tradeoff Study

The previous section explored a variety of hull options for a MK-V Replacement craft, subsequently eliminating complex hull designs or dimensionally prohibitive designs. The following section will explore options within the catamaran hull characteristics, including different pontoon designs and optimally efficient dimensions for the given speeds and draft requirements.

The first area to be studied was a hydrodynamic characteristic comparison between the catamaran and monohull. Studying the various hullform ratios and coefficients for each hull type quickly eliminated the trimaran concept because of the critical air transportability requirement mentioned above and shown in the Pugh matrix.

Monohull versus Multi-Hull

Through a comprehensive literature search, several relevant papers were discovered about the design and comparison of monohulls versus catamarans. First, in a thesis from the Webb Institute, Mr. Snediker and Mr. Telfer predict that, "compared to monohulls of equal length and displacement, catamarans have substantially more wetted surface area. For similarly shaped hulls of equal length and displacement, a catamaran's wetted surface will be around 40% greater than that of its monohull counterpart" [16]. A similar concept, related to the non-dimensionalized Froude number, is presented by General Dynamics [15]:

At low speeds (Fn < 0.35), where wave making resistance is minor, a catamaran's increased wetted surface area will result in more viscous resistance than a comparable monohull giving the catamaran a higher overall resistance. At planing speeds (Fn > 1.0), monohulls tend to have lower resistance, since the wider beam of the monohull provides a broader, more efficient planing area. The two low aspect ratio (beam / length) surfaces of the catamaran generate less lift than a single high aspect ratio surface of a monohull. However, at intermediate speeds (Fn = 0.5) monohulls typically experience a sharp increase in resistance as wave making rises. The catamaran's two slender hulls often generate less wave-making resistance than the wave making resistance of a single, broader hull.

The concepts stated above were tested using MaxSurf, a computer program for hydrodynamic modeling of ship's hulls, and is presented below with two comparable hulls and specifications to demonstrate the similarity between performance characteristics. Incidentally, the wetted surface area does not concur with the statement that a catamaran's wetted surface area will be 40% greater than a comparable monohull; comparison below suggests a 10% decrease. After rigorous investigation of the hulls and software, it is not a software error, rather a generalization that does not apply to this hull comparison.
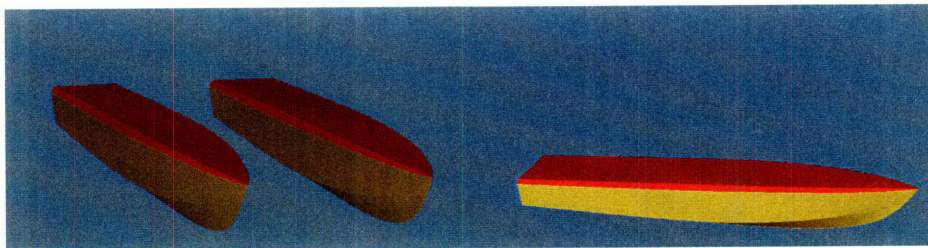

Figure 11: Resistance Validation Hullforms

Table 2: Model Specification Comparison

	Monohull	Catamaran	Unit
Displacement	65692.67	65680.38	lb
Volume	1026.63	1026.438	ft^3
Draft to Baseline	3.008	3.075	ft
Lwl	57.899	60.225	Ft
Beam	12.985	17.191	Ft
Max Sec Area	24.367	22.915	ft^2
Waterplane Area	609.517	518.774	ft^2
Cp	0.728	0.744	
Cb	0.454	0.534	
Cm	0.634	0.725	
Cwp	0.811	0.83	
RM at 1deg	10513.95	24214.865	lb.ft
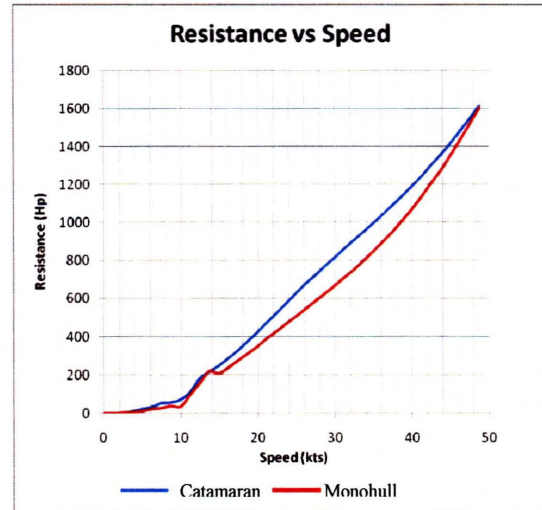
Figure 12: Resistance versus Speed Comparison

Although the results are commensurate with the expectations stated above the software does not account for two factors. First, the software used for the analysis uses slender body (strip) theory for the wetted surface area and is not capable of analyzing the reduction in wave making resistance with two smaller hulls versus a monohull design. Secondly, it is not capable of evaluating the Bernoulli Effect caused by air passing through the tunnel created by the separation between the water and crossdeck. As air passes through an airfoil shaped tunnel the differential pressure produces a lifting effect, thereby reducing the wetted surface area, hydrodynamic resistance, and the power required for desired speeds [29]. In conjunction with the advantages gained with a more thorough software analysis and even with the minimal power increase shown in Figure 12, the catamaran was deemed acceptable for dimensional analysis due to the inherent stability and high-speed capability.

Proceeding with the catamaran hull form, JMP 5.1 statistical analysis software was implemented for the Design Of Experiments (DOE). The factors chosen for evaluation are the primary dimensions of the hull form: length, beam, depth (deck

height), hull separation and displacement. Table 3 provides the relative data that was used to perform an initial analysis of catamaran hullforms. The levels, or ranges, were selected by comparison to known catamaran vessel dimensions and the current MK-V. The current MK-V's dimensions are, 85 feet long, 17.5 feet beam and a displacement of 115,000 pounds. Depth, or deck height, is the distance from the keel to the top of the deck; a dimension used to factor in the C-17 cargo compartment height limitation. Length of the future design must be less than the overall cargo compartment, plus a trailer and maintenance package. Beam accounts for the width of the engines and remaining spacing for the demi-hull separation.

Table 3: DOE Factors and Levels

|	Factor	Level		
		1	2	3
L	Length (ft)	64	70	76
W	Weight/Displacement (x 1,000 lbs)	65	90	110
B	Beam (width: ft)	5.5	6.25	7.5
D	Depth(keel-top: ft)	6	7	8
Dhull	Demi-hull Separation (ft)	7	8.125	9.25

Table 4: Initial Hullform Tests

Combination	Length	Weight	Hull Beam	Depth	Demi Sep	Response (HP)
----+	64	65	5.5	6	9.25	2426.01
-0000	64	90	6.25	7	8.125	2902.91
-+++-	64	115	7	8	7	3516.3
0-0+0	70	65	6.25	8	8.125	2648.86
00+--	70	90	7	6	7	2975.59
0+-0+	70	115	5.5	7	9.25	3568.1
+-+0-	76	65	7	7	7	2585.03
+0-++	76	90	5.5	8	9.25	3194.32
++0-0	76	115	6.25	6	8.125	3589.53

Table 4 presents the initial hull form combinations generated by the JMP software for dimensional comparison. This sample of nine, L9 matrix, combinations was automatically generated to sample the L27 (9x3) matrix. These combinations were tested using the Hydromax software for hydrodynamic analysis and the resulting resistance (power required to reach 50 knots) for each hull form. Although, demi-hull separation was expected to have a greater effect, importing the data into the JMP software confirmed the interaction that most influences catamaran design is displacement. Figure 13 below shows the tight grouping of displacement data relative to the resistance required to propel the vessel at 35 knots. Figure 14 shows the same resistance data relative to the length, depth, and catamaran hull spacing for 35 knots. The standard deviation charts below each provide an axis for comparison of each factor; the higher standard deviation, the less dominant a factor in the design. It should be noted that any speed above the wave-making speed (12 - 15 knots for this hull design) referenced in the next paragraph shows virtually the same relationships.
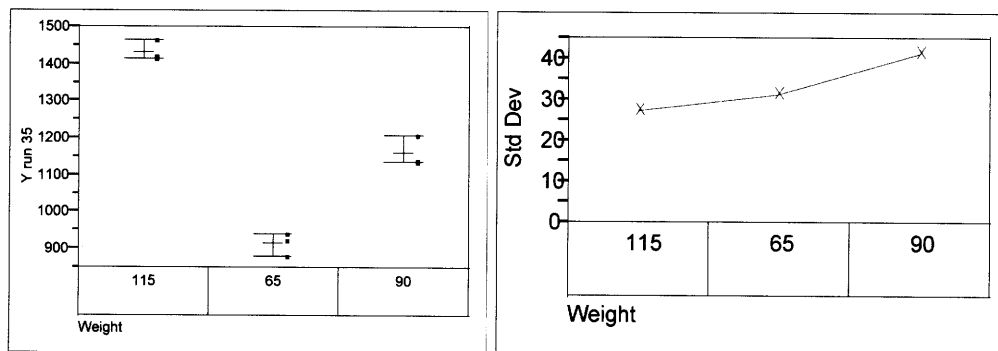
Figure 13: Displacement Variability and Standard Deviation
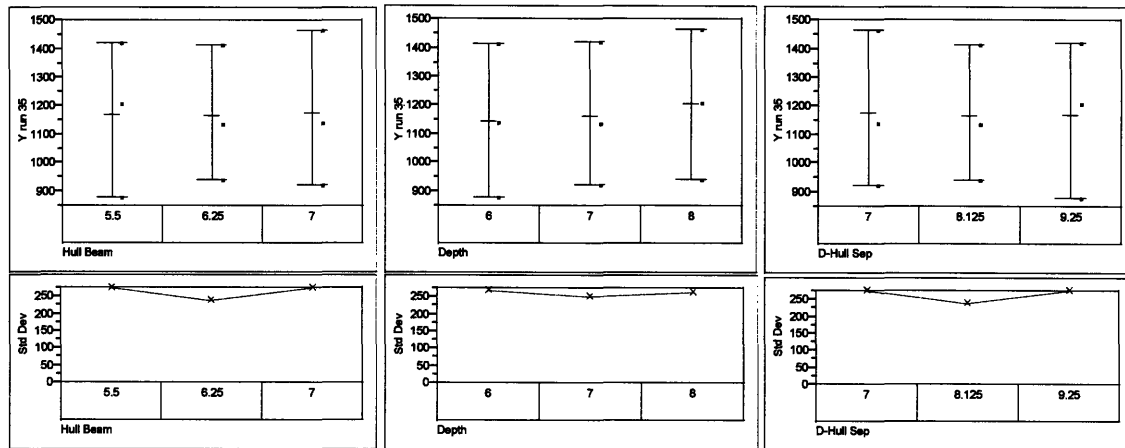
Figure 14: Beam, Depth, Hull Separation Variability and Std. Dev.

A HydroComp, Inc. report [10] stated that, "hull spacing has shown to have the most effect on interference resistance in the lower speed ranges (below 20 knots) near the principle wave-making hump speed. Above this speed regime, there is little difference in added interference drag due to hull spacing." Figure 15 shows the wave-making hump occurring at 12-15 knots; below 10 knots the design is dictated by the hull spacing, but requires relatively little power. This discovery removed the low speed regime from the primary analysis. However, above this range and up to 50 knots, this design shows greater response to changes in displacement, the differentiator in Figure 15, and results indicate much higher power requirements for corresponding speeds. The higher speed requirements dictated further considerations due to the high-speed operating profile. Further analysis was completed with a fixed beam, 17.5 feet, and length, 64 feet, while the individual hull width and height were modified. The beam was selected for the maximum feasible width of the C-17 cargo compartment, while the length was chosen to include a maintenance package and trailer to fit inside the C-17. These results are discussed in Section 3.6.
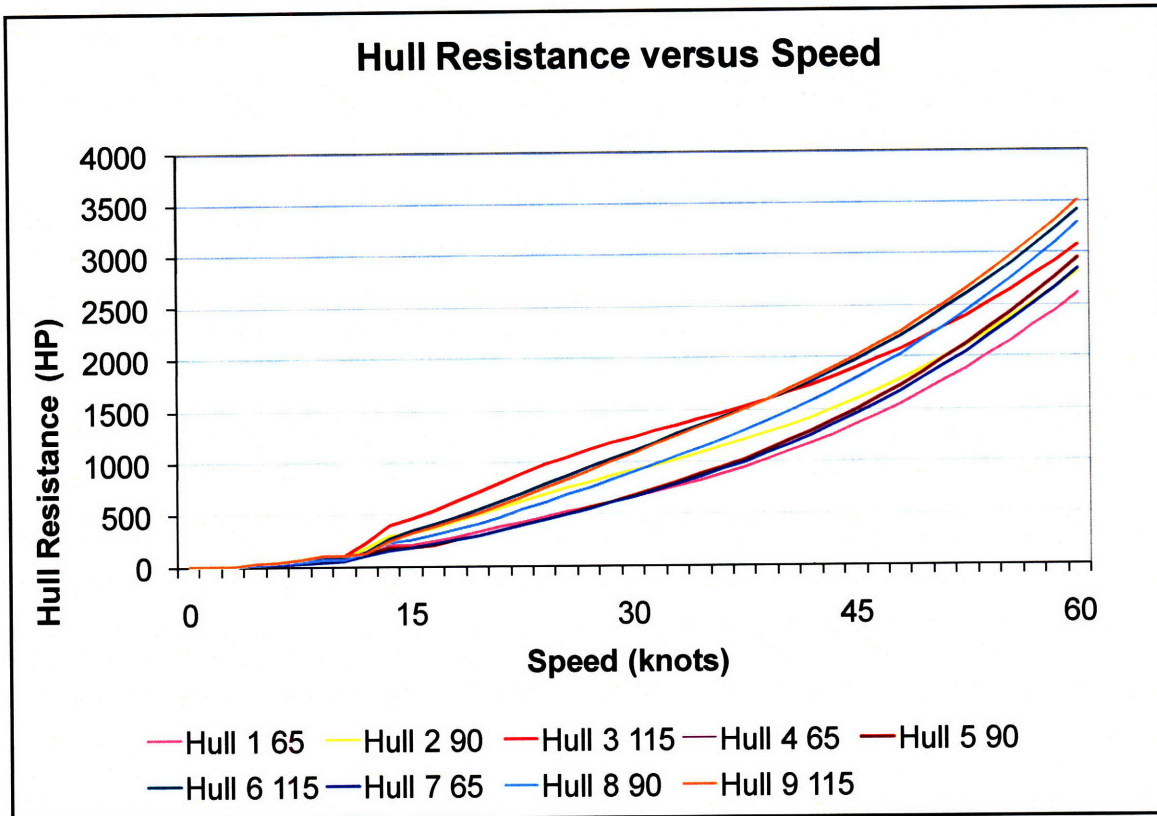
Figure 15: Initial Hullform Speed Power Curve

3.5 2nd Pugh Concept Convergence: Initial Concept Design

Using the catamaran hull examined above led to an initial concept design as shown below. Figure 16 shows the basic break down of hull compartments for the concept at this stage. Figure 17 illustrates the hull spacing, demi-hull width, height, and overall beam of the ship. The rough layout provides a visual check of the feasibility of the design and evidence that further consideration has merit.

The next round of analysis varies the hull shape to determine the best design for hydrodynamic resistance.
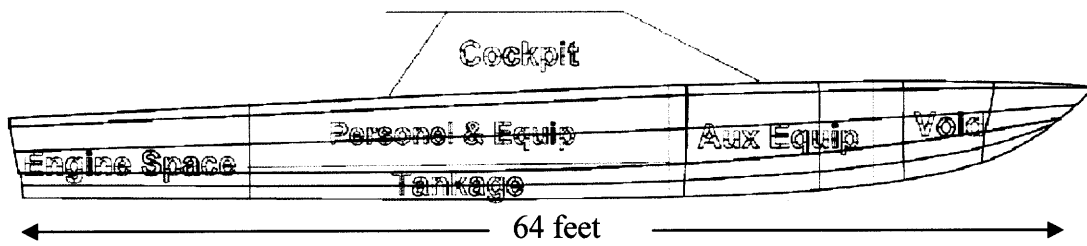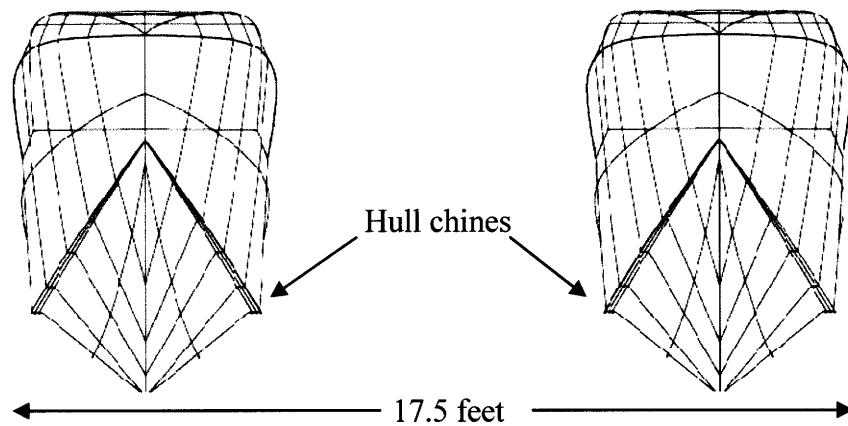
Figure 16: Initial Profile and Layout

Hull chines

17.5 feet

Figure 17: Initial Hull Plan (Symmetric Catamaran)

3.6 3rd Pugh Concept Generation: Second Catamaran Analysis

The next iteration of the catamaran hull design study evaluates the catamaran hull forms according to the procedure to modify the shape of the demihulls as described in the paper "Resistance and Propulsion Characteristics of the VWS Hard Chine Catamaran Hull Series" [18]. The four step procedure modifies the catamaran hullforms in three ways, symmetric design (Figure 17 - above), semi-symmetric, no sides, and compares each to the monohull of equal measurements; 64 feet length, 17.5 feet beam, 8 feet height, and 90,000 pound displacement (Figure 18).
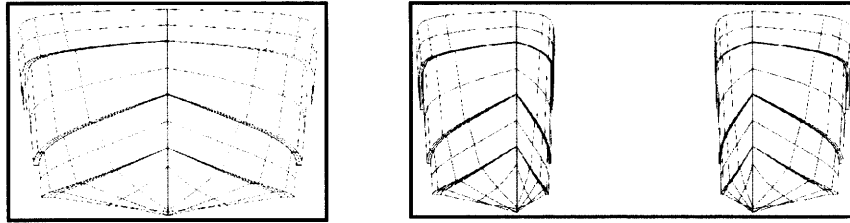
Figure 18: Monohull and Semi-symmetric Catamaran
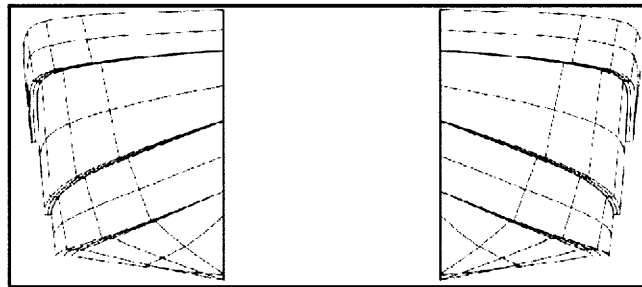
Figure 19: No-Side Catamaran Hull

A semi-symmetric design modifies the inner hull walls to angle up at a sharper angle than the symmetric design shown below. The No-Side design pictured in Figure 18 has a vertical inner hull shape with the same outer hull as the symmetric hullform. Using two different hull types, a smooth hull obtained from MaxSurf and a hard-chined hull (Figure 17) provided by Brett Bakewell-White of Bakewell-White Yacht Design [17], the catamarans were tested for resistance and plotted against a monohull of similar dimensions (Figure 20). Even though the MaxSurf model, labeled "simple," has the least resistance of all the catamaran designs, due to the accuracy of the model provided by Mr. Bakewell-White, the hard-chined hullforms, labeled "advanced" in Figure 20, will be used throughout the rest of this study. The data gained from this experiment proved that the semi-symmetric catamaran hulls required lower power than other models to meet the high speed regime needed for the MK-V Replacement vessel. Additionally, the advanced, hard-chined hullform will provide the lowest vertical accelerations [18].

Special consideration should be taken when examining the spike in the lower speed range. Although the power requirement in the low speed regime is not a primary

concern with vessels capable of 50 knots, this anomaly is attributed to the inaccuracies of the MaxSurf HullSpeed software application using strip theory to evaluate resistance for the catamaran hull. At higher speeds, the Savitsky method was used to evaluate the catamaran hulls in the planing regime and provides very consistent data for each model. These consistencies provide assurance to the accuracies of the data above 15 knots.
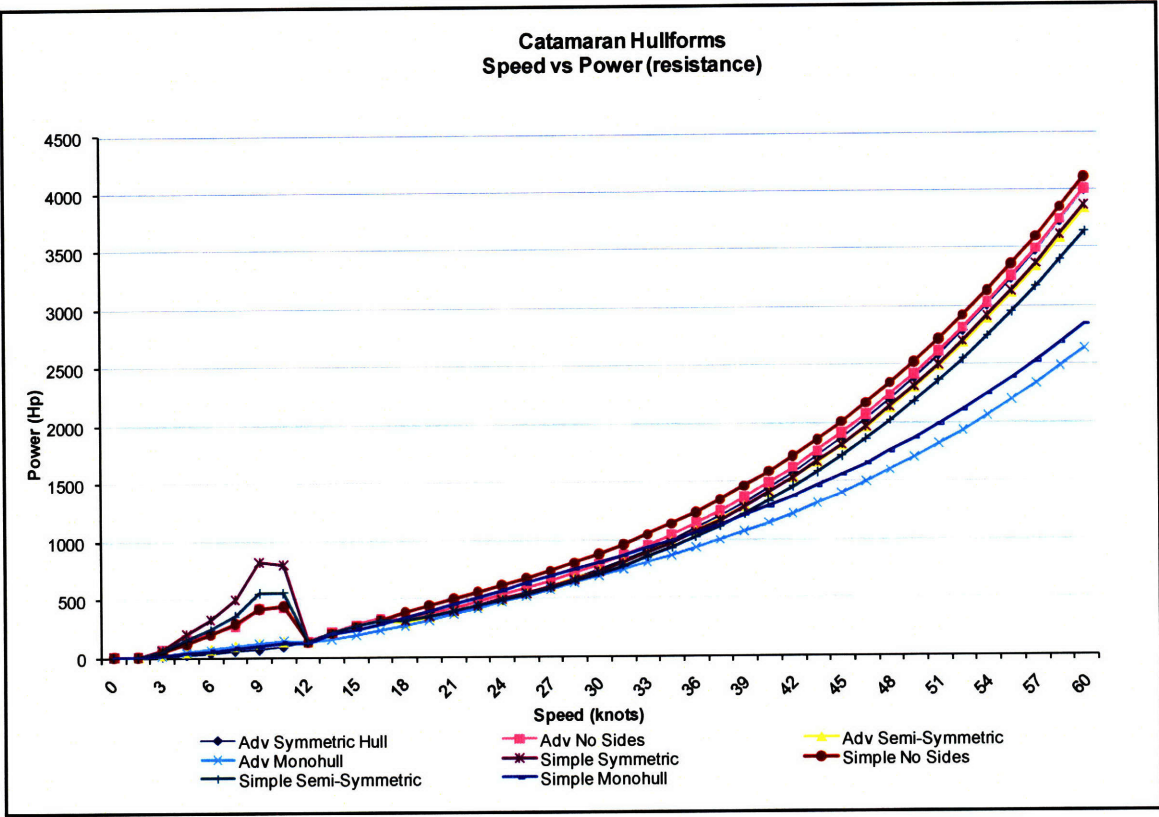

Figure 20: Catamaran Hullform Comparison

3.7 3rd Pugh Convergence: Hull Form Summary

Table 5 shows the relationship of each of the advanced hull forms with respect to each of the parameters that materialized through the research and experimentation. The team discovered that resistance is least with the semi-symmetric hullform at all speeds as

well as providing the added benefit of better seakeeping due to the dampening effect of the hullform. Seakeeping was determined qualitatively from evidence provided in literature research [16]. Additional ride comfort measures were incorporated into the design with the use of the advanced, hard-chined hull design and raising the crossdeck height to the maximum allowable to prevent wave impact with the crossdeck.
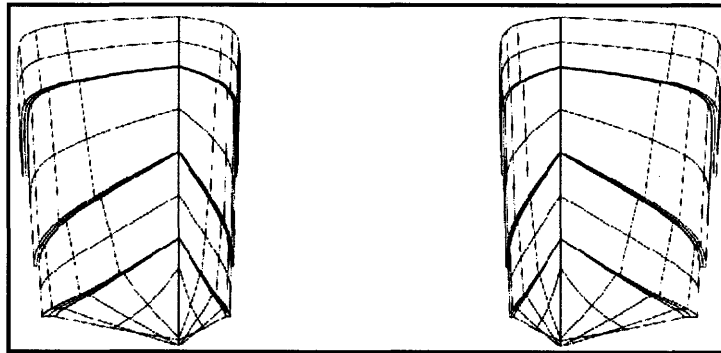
Figure 21: Semi-Symmetric Hullform

The method used for quantitatively evaluating each of the options is shown in Table 5. The categories across the top correspond to a weighted measure of effectiveness by which each design, (symmetric, semi-symmetric, and no-side) was quantitatively evaluated. Similar to the Pugh matrix, the option with the best characteristic was rated with a '1' and a green box; the second was given a '0.5' and a yellow box; third ranked lowest with a '0' and is denoted with a red square. Those values were then multiplied by the weighting factor across the top of the table under each category. The weighted values were then added horizontally across to give a total for the particular hull design. The ranking can then be used for further system level integration analysis. The semi-symmetric hullform pictured in Figure 21 does have a clear advantage over the other hull designs.

Table 5: Hull Form Selection

	Resistance		SeaKeeping (ride comfort)	Dimensions			Total (high is better)	
	35 knots	50 knots		Useable Volume	Draft	Beam		
Weighting (importance)	0.15	0.2	0.3	0.15	0.1	0.1	=>	1
Symmetric	0.5	0.5	0.5	0.5	0.5	0.5	=>	0.5
	0.075	0.1	0.15	0.075	0.05	0.05		
Semi Symmetric	1	1	1	0	0	0	=>	0.65
	0.15	0.2	0.3	0	0	0		
No-Side	0	0	0	1	1	1	=>	0.35
	0	0	0	0.15	0.1	0.1		

3.8 Summary

Continuing with the iterative design spiral theory and analyzing interactions between system components, such as the hull material or propulsion plant where more than three options exist, the same ranking methodology may be used. This philosophy allows the combinations of system components including the main propulsion engine, hull material, and propulsor to establish the most feasible working combination for the design of a robust system capable of effectively and efficiently completing the mission. By combining this ranking method with similar methods for other components, the overall effectiveness may be measured and evaluated in order to determine the best solution for a given problem space.

CHAPTER

4

PARAMETRIC VALIDATION

4.1 Introduction

Validation of the achieved design is perhaps one of the most important aspects in the design spiral, which should occur as a reflection on the results and modification of the process [9]. This analysis should determine the feasibility of the design and determine if it satisfies the operational objectives to meet the stated need [5]. Validation can occur as a simple a measure of effectiveness for the final design or a parametric comparison to known solutions. However, as complexity increases, only preliminary validation can be expected from parametrics before exploratory development and experimentation should take place.

Depending on the system or combinations of systems evaluated, one method may work better than the other. Using the example in Chapter 3, the hull design lends itself to parametric evaluation due to the size, speed requirement, and the vast number of examples of catamarans in service. Additionally, the design must be feasible such as validating the power required to reach required speeds for the vessel; i.e. "does the engine fit inside the hull" or "does the selected engine have enough power to propel the vessel?" This type of evaluation should be assessed through further experimentation and eventual exploratory development of hull models.

The design spiral shows interactions and relative interdependence of key design parameters such as the effect of changing displacement as it affects all other aspects of

the design. Graphically, validation happens at the extreme center of the design spiral once all pieces of the system have been chosen and their interdependencies addressed. In particular, the validation process should answer the question, "does this design address the issues of the customers?"

4.2 Design Validation

In the hull design validation process there are relatively few areas to consider to validate the catamaran design; however, the most prevalent dimensions are length overall (LOA) and beam. Initially, a beam of 17.5 feet was selected based on the C-17 transportability requirement and length was determined to be 64 feet on the waterline. In order to meet the mission objectives and additional 6 feet long ramp was constructed on the back of the vessel providing an overall length of 70 feet.

Parametric Validation

Figure 22, plots the design dimensions versus similar catamaran designs. The large grouping signifies traditional catamarans used for high-speed ferry service, typically capable of 30-40 knots. The small grouping, with characteristically narrow beams, is high-speed racing catamarans known for speeds in excess of 125 knots. The MK-V Replacement design falls at the low end of the ferry designs with a narrower beam. The graph should be interpreted with the lower speed vessels in the upper right and higher speeds attained by the vessels in the lower left; thus, the location of the MK-V Replacement design is expected with the speed variation between the two categories.
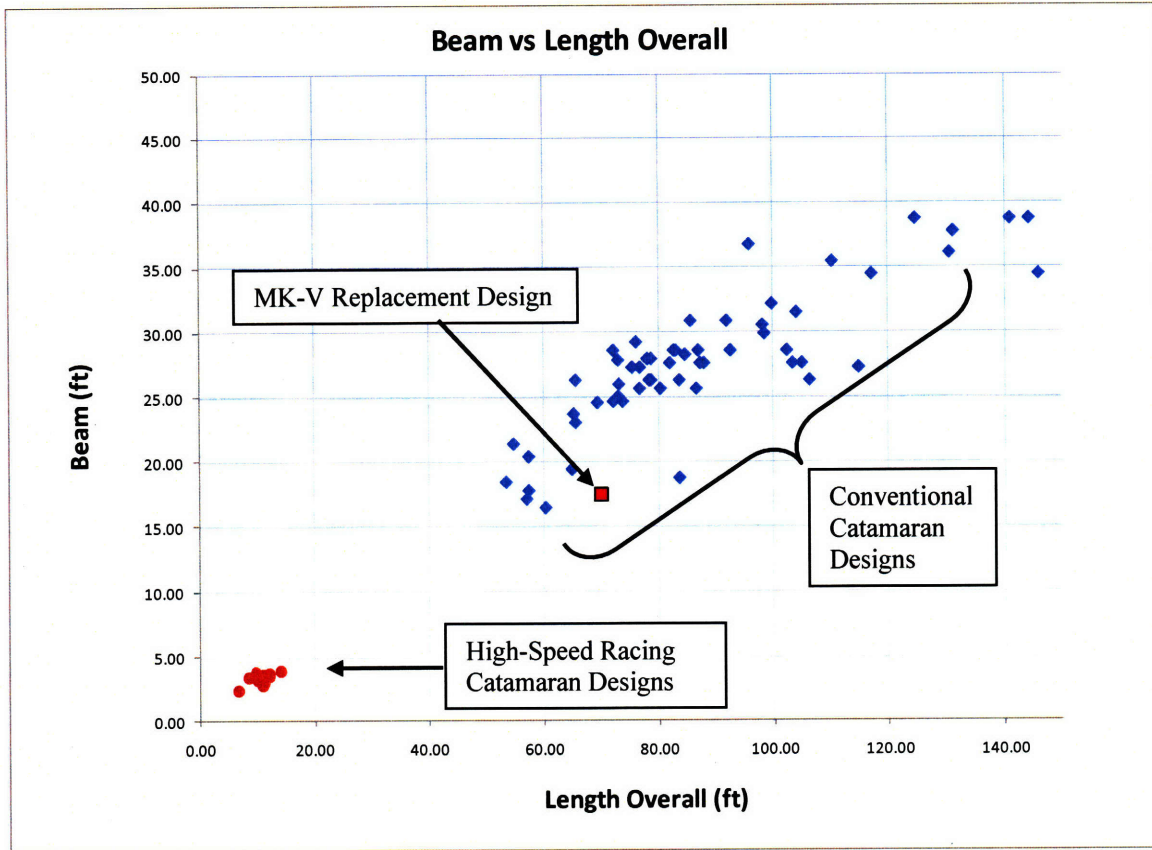
Figure 22: Beam versus Length Overall Parametric Data

Figure 23 shows the hull separation versus length. Unfortunately, there is very little published data concerning vessel dimensions that includes hull separation. The vessels plotted below include two high-speed ferries (30-40 knots), three offshore racing catamarans (+140 knots), and the MK-V Replacement design (57 knots). As expected, MK-V Replacement falls between the two different catamaran speed profiles. The slightly narrow beam, as mentioned in Section 3.4, will induce greater wave making resistance at lower speeds, but will not affect the vessel at speeds above 20 knots.

Hull Separation vs Length
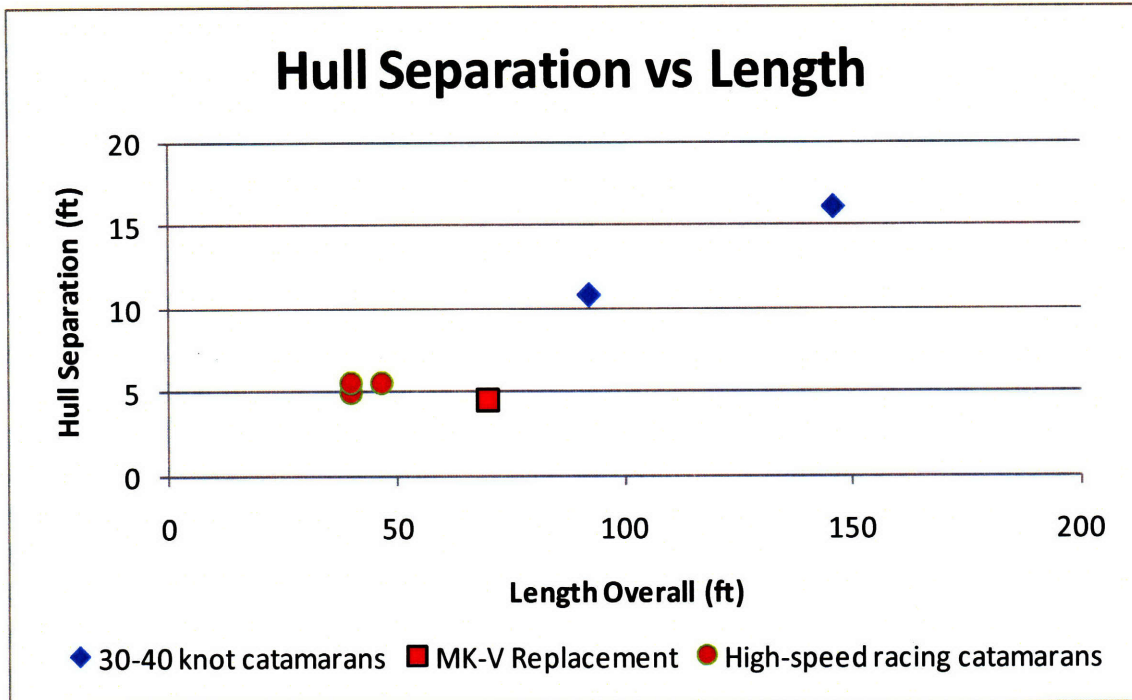
Figure 23: Parametric Hull Separation versus Length

Figure 24 shows similar data concerning the primary design factor, displacement or weight. The catamaran data was filtered to restrict the weight analysis to vessels between 10 and 73 long tons and then plotted against speed. The findings show that non-military vessels are usually limited to less than 40 knots, while military vessels, such as the current MK-V and the MK-V Replacement design, are required to achieve speeds in excess of 50 knots. Vessels of this nature must also have the associated power plants to propel them to speeds above 50 knots. This inherently leads to engines slightly larger than those on commercial vessels resulting in hull separation less than commonly observed, as Figure 23 shows.
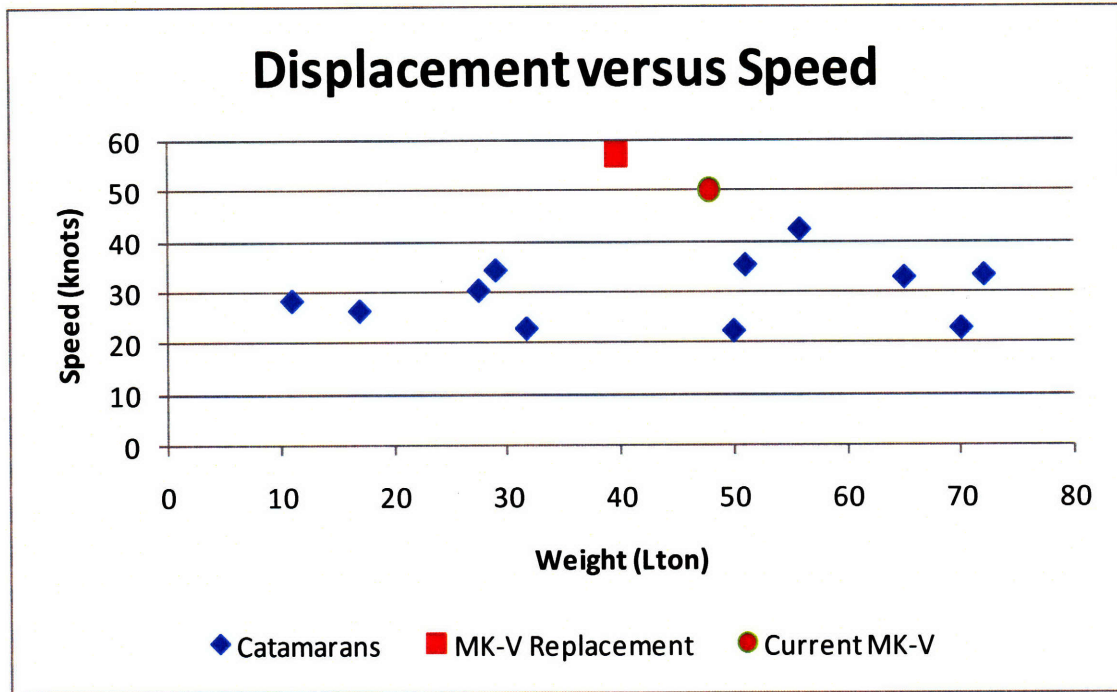
Figure 24: Parametric Displacement versus Speed

Design Feasibility

In order to determine the design's feasibility, the vessel must have an attainable power curve for the customer's speed requirements. Figure 25 plots the power curve results attained from hull testing using the Hydromax software. Further design iterations would require an engine selection that can generate the power required to match the maximum required speed for the speed profile and fit inside the engine compartment. The engine compartment is defined according to design rules specified by oversight agencies - stakeholders - such as the American Bureau of Shipping (ABS) and Naval construction standards. In this case, the engine compartment width is 6.5 feet, which allows for a 5.5 feet wide engine. For example, the MTU series engine, a likely engine selection, has a width of 4.72 feet. In keeping with the design spiral methodology, additional consideration should be given to the fuel efficiency of the engines and the

volume of fuel required to meet the customer's desired range; all of which will have volume and weight implications on the design.
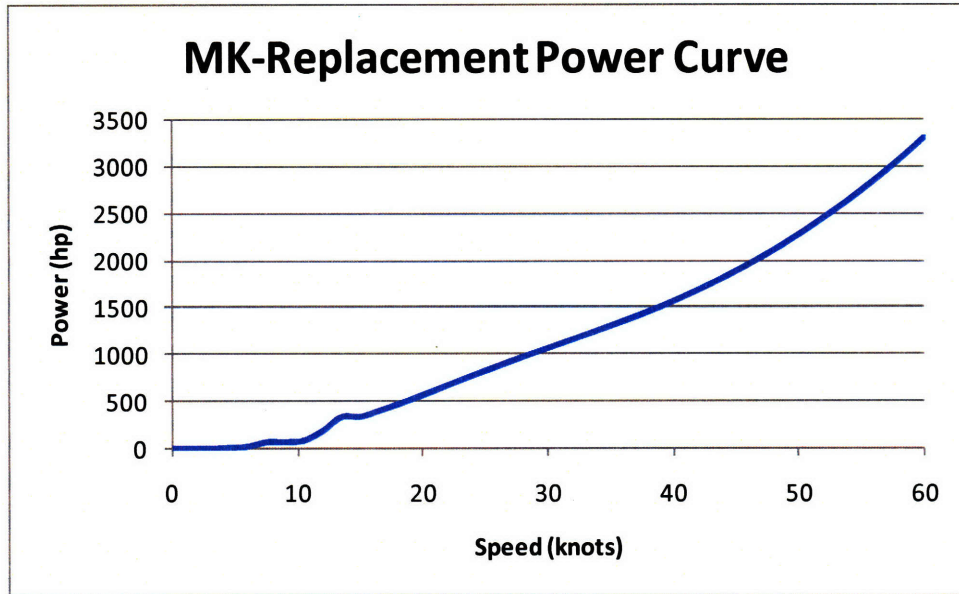

Figure 25: MK-V Replacement Power Curve

Design Vessel Behavior in the Operating Environment

One of the core attributes that required improvement over the current design was the reduction in slamming effects on the crew of the MK-V, Section 3.2.3. Table 6 provides the International Standards Organization (ISO) limitations for the effect of vertical acceleration on the occupants caused by slamming. According to this table, the MK-V should be limited to 1.0 g above the static measurement. Static measurement is considered the force of gravity observed by the vessel at rest in calm seas. Beyond that limit, the possibility of fatigue and discomfort exist as well as an increased propensity for injuries.

Table 6: Effects of Vertical Acceleration [32]

g's Above Static	Affects Personnel	Application for Structural Design	Material Stress Level for Bottom Structure	
			Fatigue	Short Term
0.6	minor discomfort	craft for (fare-paying) passenger transport	x	
1.0	maximum for military function long term (over 4 hr)			
1.5	maximum for military function short duration (1-2 hr)			
2.0	tests discontinued	patrol boat crews, average owners	x	
3.0	extreme discomfort	test crews, tournament sportfishermen, long races	x	
4.0		medium-length races	x	
5.0	physical injury	race boat drivers, short races		
6.0		military crew under fire		x

NOTE: Acceleration levels (g's above static) refer to the average of the 10 highest at the center of gravity of the craft.

Using another feature of the Hydromax software, the following plots were made depicting the vertical accelerations at the furthest point from the center of gravity; the extreme forward corner. In this analysis, the right forward corner was chosen for analysis due to preference; either corner will provide the same results within a fraction of each other.

Figure 26 provides the results for cases involving incident wave angle from all cardinal directions relative to the vessel. The customer stated a need of 45 knots in Sea State 2, shown on the left, and 30 knots in Sea State 3, on the right. The vertical axis, annotated with the g-forces above the origin, represents accelerations from waves encountered directly ahead, above the origin, and behind the vessel, below the origin. In all cases, the MK-V Replacement design vertical acceleration is below 1.0 g, which is acceptable according to the stated ISO standards.
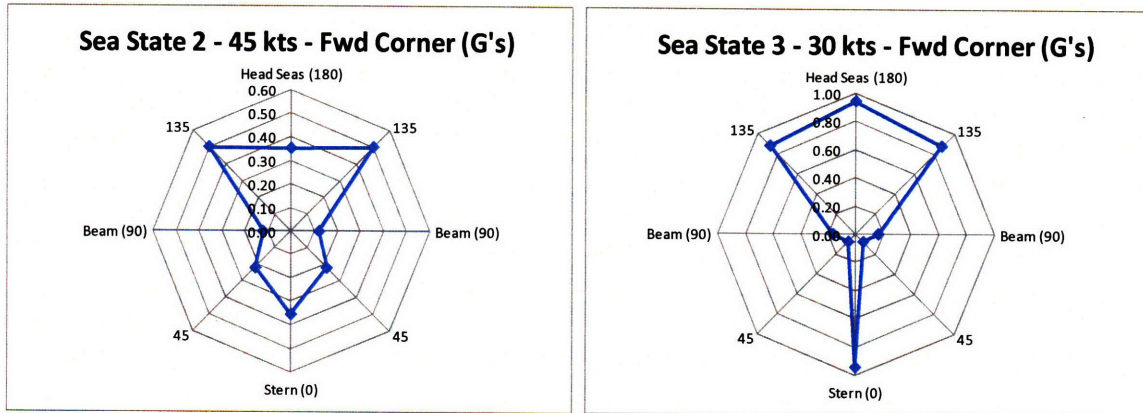
Figure 26: MK-V Replacement Vertical Accelerations

4.3 Summary

In complex systems, system validation models can be developed to ensure the feasibility of the model in construction and in the operating environment. The previous discussion has focused on three models to validate the potential of the MK-V Replacement design. First, parametric evaluation was used to ensure that the vessels falls within acceptable dimensional ranges as compared to vessels capable of similar or greater speeds. Second the model was evaluated for feasibility to determine if the capability includes the customer's speed requirement. Finally, the design was tested for operation in a specified environment per the customer's needs. In all cases or through further design iterations such as with the engine selection, the MK-V meets the stated objectives.

Validating the exercise is one of the more important aspects of the design process. Early in the concept design phase, the effectiveness models, similar to that used in Table 5, can be used in combination with models developed for other systems to evaluate the total effectiveness of the combined systems. Delaying validation of the system or combinations, whether theoretical or through experimentation, presents specific problems with new technologies. Technologies that cannot be fully replicated in the theoretical

environment or have not been tested, such as the EMALS mentioned in Section 2.3.2, require demonstration on production platforms to prove their feasibility in an operational environment.

5

FUTURE RESEARCH & CONCLUSIONS

5.1 Future Research

This thesis had addressed the concept of designing a new vessel using currently available methods for small vessel design in naval architecture. While the example provides several methods, including the iterative design spiral and Pugh matrix, it does not use every method available. Currently, research is needed in several design areas such as genetic algorithms, modularity, and the interdependence of cost versus design flexibility to develop future capabilities at a reasonable cost.

Real Options incorporated into the ship's designed service life

The U.S. Navy is currently at a cross roads with the philosophy of naval vessel design and construction. On one hand, the stated high-level strategic objective is a 313 ship Navy, yet the pace for construction falls well short of that over the next decade. The current design mentality is to build ships with a 35-40 year service life. However, several ship classes have been decommissioned at 23 years, including Frigates, Destroyers, and Cruisers, [33].

Though much speculation arises for such early retirement there are many reasons. First, ship's age rapidly and tend to deteriorate in a saltwater environment. Second, the need to maintain a ship building work force that is capable of meeting the demand when it is needed. Thus, by retiring ships early, the government generates a need to build ships

that keep the capability within the United States. Third, the systems are out-dated and need replacing with more current technologies. Specifically, weapons systems need updating to maintain fleet capabilities; thus far, the aircraft carrier possesses the only truly modular weapons system in the Navy's arsenal; the aircraft. Incidentally, the aircraft carrier is the one of the few surface combatants to meet or exceed the expected service life. This illustrates a need to develop a modularity model that can accommodate technology updates into the ship's service life in order to extend the useful life of the ship beyond the average 23 years.

Similarly, there need exists to assess a monetary value on modularity to assist the decision makers in recognizing the "real option" of putting a ship into service not just with room for expansion, but rather to plan for systems swap later in life when new technologies or threats arise. Just as the aircraft carrier is not particular to the aircraft that operate from its' deck during deployments and aircraft are only platforms to transport weapons, ships should be considered platforms to carry weapons systems. This concept can apply to navigation systems, engine monitoring systems, and, most importantly, weapons systems. Weapons systems, in the Navy, are typically the most important system on the ship by the nature of the vessel; a war ship.

Such a real options model must be able to produce a future monetary value on modularity, assess the cost effectiveness of modularity to enable future flexibility, and determine how to incorporate the product oriented design and construction cost model into the standard way of performing cost estimation. The future of naval vessel design is in modularity; one way of incorporating that is through the use of genetic algorithms.

Genetic Algorithms

The current mainstay of large vessel design is a software program called ASSET, which was developed for the U.S. Navy to use during the concept exploration design

phase. Through a series of user interface windows, the program allows the designer to select certain components or dimensions that are desired in a ship, typically greater than 150 feet in length. Once all the inputs have been entered, the program will iteratively "build" the ship. Unfortunately, the result is only as good as the inputs and, at times, the design does not "converge" to the center of the design spiral due to any number of factors; i.e. one engine not capable of the speed requirement, larger range than fuel on board, etc.. These characteristics prevent the software from finding new solutions and typically cause errors in the modeling process.

The use of genetic algorithms should be explored with the underlying possibility of developing an accurate computer model that will provide a design based on stated parameters. Genetic algorithms are software programs that begin with a broad selection of options within a population (similar to the Pugh concept), where selection of characteristics can be made via several generations or iterations to determine the best characteristics for the whole system [34]. The most interesting attribute of a genetic algorithm is the ability of the program to "combine" or "mutate" characteristics to find a more optimal solution, a way around a problem, or an increased level of effectiveness. While some attempt has been made to develop and use programs of this nature, there is little success in applications to naval vessels.

5.2 Conclusions

This thesis has provided an example of high-speed naval craft design and has illustrated the advantages of combining several design tools presented during the course of study in the System Design and Management program. The example in Chapter 3 explored the use of the design spiral and Pugh concept selection process, while validation of the model was achieved parametrically and by using software experimentation to evaluate the design in an operating environment.

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