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A capability-based, meta-model approach to combatant ship design

Fox, Jason P.

Monterey, California. Naval Postgraduate School

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A CAPABILITY-BASED, META-MODEL APPROACH TO COMBATANT SHIP DESIGN

by

Jason Fox

March 2011

Thesis Advisor:	Clifford Whitcomb
Second Reader:	Eugene Paulo

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Using a simple medium-tonnage patrol vessel and a Maritime Intercept Operation (MIO) mission in a fictional setting, operational and ship design synthesis models are developed. Critical design criteria (responses) in each model are measured using relevant design variables (factors) based on mission measures of performance used in creating experimental designs. The resulting models are then linked, both mathematically and using graphs, to show how decisions made by the naval architect can directly influence a single operational measure of effectiveness. Decision makers can then assess various system outcomes by trading off performance parameters to make capability-based decisions.

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Jason P. Fox
Lieutenant Commander, United States Navy
B.S., United States Naval Academy, 1998
M.S., Naval Postgraduate School, 2003

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requirements for the degree of

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NAVAL POSTGRADUATE SCHOOL
March 2011

Author: Jason Fox

Approved by: Clifford Whitcomb
Thesis Advisor

Eugene Paulo
Second Reader

Clifford Whitcomb
Chair, Department of Systems Engineering

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LIST OF ACRONYMS AND ABBREVIATIONS

ASNE	American Society of Naval Engineers
DES	Discrete Event Simulation
DRM	Design Reference Mission
DOE	Design of Experiments
DoD	Department of Defense
DOTMLPF	Doctrine Organization Training Materiel Leadership Personnel Facilities
HM&E	Hull, Mechanical, & Electrical
INCOSE	International Council on Systems Engineering
MBSE	Model-based Systems Engineering
MOE	Measure of Effectiveness
MOP	Measure of Performance
OA	Operations Analysis
OPSIT	Operational Situation
OR	Operations Research
UJTL	Universal Joint Task List
UNTL	Universal Naval Task List

Naval Architecture and Combat System Specific Symbols and Terms

B	Beam
C_P	Prismatic Coefficient
C_X	Maximum-transverse-section coefficient
GHz	Gigahertz
GM/B	Transverse metacentric height to beam ratio (an indicator of stability)

hp	horsepower
knt	Knor
kW	kilowatt
LWL	Load (or design) Waterline
MHz	Megahertz
T	Draft
Δ	Displacement

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I. INTRODUCTION

A combatant vessel is arguably one of the most complex weapons systems produced. So much so, that the time to deliver an initial ship of a class can sometimes be measured in *decades.* For this reason—among many—Navies by necessity seek ways to improve the process used to estimate and predict the various design and construction impacts on warships early in the design phase and throughout development.

Historically, the design process has tended to be a compartmentalized, partitioning naval architecture, combat systems, and weapons into distinct process with minimal overlap in the initial design phases. For example, a combat systems suite might be designed to meet a particular threat or mission area, and then the hull form is designed around and constrained by it. Or a new ship is designed based on an incompletely known or understood requirement for the combat system in terms of size, weight, power, and other factors, and the design is "adjusted" later in the process to fit the desired warfighting capability. Then, as the design of both mature, changes become increasingly difficult and costly to incorporate, coordinate or make at all, yet remain unavoidable.

An often-cited example by Mr. Robert Keane might be the design of the DDG 51 class destroyer. The ship design focused on the AEGIS Combat System. However, many physical aspects of the hull, such as displacement and length to beam ratio, were constrained by law, which led to a series design modifications that ultimately resulted in a less efficient hull-form in order to accommodate the required combat systems payload. Effectively this forced the design team to make these changes without consideration of the operational effectiveness of the platform, and "sea keeping ability" became dominant as the primary measure of effectiveness throughout the design (Whitcomb 1998).

The complexity and length of the design-to-deliver process creates further problems. In the case of the ZUMWALT class destroyer, a ship which remains at least 1 year from delivery as of this writing, has been in development for nearly 20 years. The world stage has and will continue to change significantly, and the military needs that generated the initial designs are likely to adjust in relative weight to one another. The costs for the Department of Defense to adjust or abandon the project become prohibitive, and at best, the Navy is left with a ship that it no longer needs.

In light of this, it would be beneficial to understand the impacts of hull and combat system designs on the anticipated operational effectiveness of the final product as early in the design process as possible. There are two reasons for this: first, if the ship is designed using this model initially, then presumably all future design decisions and changes could be understood in terms of ultimate operational effectiveness, enabling informed decisions throughout the process. Second, by fully understanding and exploring the design space early in the process, it is conceivable that major delays resulting from late changes will be minimized, thereby shortening the delivery time.

This is much easier said than done. One approach to doing this is might be to rapid-prototype a ship to test, measure, and adjust the design. However, building full size ship prototypes is prohibitively expensive and takes a substantial amount of time. This tends to drive the early design process to computer-based modeling and simulation. However, modeling how a particular weapons system would perform in a given combat scenario and modeling the performance of a hull form are enormously difficult challenges in their own right, even when done independently.

By applying a Systems Engineering approach to naval combatant system design, it should be possible to model both the combat system in a operational setting and the hull design. It should then also be possible to show the linkages between those models if they are developed with common technical measures. If the links are valid, the models together should show how changes in one model effect the outcome of the other.

This research sets out to do that, albeit on a very small scale. Using traditional Systems Engineering tools such as discrete event simulation, design of experiments, and response surface methods, it seeks to show a process of producing a cost-effective design of a basic combatant ship. The ship is simple in that it will only perform a single mission. The intent is to show that the design focus is primarily on the measures of effectiveness for that mission, rather than by constraints on the dimensions or characteristics related to the movement (speed, stability, *et cetera*) or size of the vessel.

A. HISTORIC BACKGROUND

The design of warships for the U.S. Navy enjoys a rich history dating back to Joshua Humphries' designing the first six frigates for a young nation's Navy in the late 18th century. Entire books could be dedicated to this subject alone: however, for understanding the context of this thesis, a brief discussion of the history of combatant ship design methodology in the 20th century is necessary. The information presented here is a summary of personal discussions with Captain Charles Calvano, USN (ret), former head of the Navy's ship design office, and various presentations and discussions presented at the American Society of Naval Engineer's (ASNE) Engineering the Total Ship Symposium in July 2010 and ASNE Day Symposium in February of 2011.

The ship design office—then a part of the Bureau of Ships—would design the majority of the ships that would win World War II. Highly buildable, detailed designs were turned out quickly. After the war, their basic methodology would evolve such that a team of Naval Architects would constantly work on conceptual designs for ships, exploring design spaces, and generating sets of particular class of ship designs. When a new requirement for a ship was generated, one of these conceptual designs could be "pulled off the shelf," a cross-discipline team assembled, and a preliminary design generated. After clearing the next acquisition milestone, a contract design was produced, and then the shipbuilding industry would produce the detailed design. The Navy procured the majority of the ships in service today this (with the exception of the LHAs) (Keane, 2010).

In the early 1990s, Congress directed the Navy to procure ships following the basic model that the bulk of the Department of Defense used for all other acquisition programs. Essentially, this would put the onus for the total design of the ships on the shipbuilders, a task they were not ready to take on.

Following that, the workforce in the ship design office was drastically cut, down to about 300 in the late 90s from 1,250 a decade earlier (Keane, 2009). While there have been some acquisition successes since then (most notably the T-AKE class of logistics ships—built largely to commercial standards), the two major combatants in procurement since then—the DDG1000 and the Littoral Combat Ship—have been fraught with massive delays and tremendous budget-overruns. While there is no single cause to pin this problem on, the lack of direct, experienced government involvement in the designs is often cited as one of many reasons among professional circles.

The Navy has begun to take steps to correct this problem. While it is no longer possible to go back, there have been several initiatives recently to make a course correction. Some of these include greater government-contractor collaboration, inventive contracting initiatives, and extensive research in new design methodologies. There have also been several efforts to reconstitute the professional experience within the government, to include standing up the Center for Innovation in Ship Design (CISD) within the Office of Naval Research (ONR), the NPS Total Ship System Engineering (TSSE) program, and the Naval Engineering Education Center (NEEC). The latter is a consortium of the major Naval Engineering Schools and Societies based at the University of Michigan.

Many of the results of these initiatives include new and innovative ways to apply design theories from other industries and innovative ways to use traditional Systems Engineering tools and practices. Many of them take advantage of the dramatic and continuing increases in computer power (Wolff, 2000). It is in this vein that this thesis seeks to show a practical application of a proposed ship design method.

B. RESEARCH QUESTIONS

The history of ship design as the author has come to understand through research and conversations with leaders in the field have lead to a series of questions that arise naturally. This thesis intends to address at least one such primary question and three secondary questions related to it.

First, from the background, it is clear that there is not a very strong link in present design practice between the development of the hull (HM&E) and the combat system. There, the primary question is, “Can a process to design a ship be shown that includes the linkages between traditional First Principles of Naval Architecture to mission effectiveness?”

The secondary questions stem from the above and address a potential methodological approach. Those questions are:

Can an operational model of a Maritime Interception Operations (MIO) be developed that can show the potential mission effectiveness of a design concept?

Can a ship synthesis model be developed that can model the design responses to similar factors as the operational model?

Can the two models be linked in a meta-model to show linkages between ship design considerations and operational performance?

The MIO mission was selected because it is relatively simple in nature, is well understood, and the operational model is straightforward. Further, for an operational model, it addresses a shortfall in mission design in the Gomez-Torres thesis (discussed in detail below), as well as addresses a mission area of interest to the international ship design and building community.

C. SYSTEMS ENGINEERING APPROACH

In the broadest sense, this thesis is clearly a model-based systems engineering (MBSE) approach to engineering a system. MBSE is simply the application of any of a large class of models (Physical, Quantitative, Qualitative, and Mental) to aid in the design of a system (Buede, 2009). Buede argues that in general, the models should start with a high-level view that addresses the needs of the system, and then progress through modeling levels of how that system will meet those needs. He would also probably argue that "everything is a model" until the system is actually built. There is likely a lot of truth to this.

At the top level of the approach presented here is essentially Forsberg and Mooz's "Vee" process model (Blanchard and Fabrycky, 2006). This is a higher-order view that address in general terms how a system design should progress from requirements identification to design, to building, and through testing.

Apart from its general acceptance and applicability to the Department of Defense's acquisition process, this design approach seems particularly well suited to the nature of the "Vee." Specifically, as the design proceeds down the left side, design decisions are made using models that are based on capabilities. As the testing, verification and validation process proceeds up the right side, testers, customers, and end users will largely care about the demonstrated performance and capability of they system. If the capabilities of the platform are identified and used to guide modeling from the start, then the design should, if done correctly, achieve the desired capabilities. There are many variations of the "vee" in use today. This research does not seek to propose a new one, only to show its general applicability in a broad sense as an over-arching design process.

Some variants of the "vee" start with identifying the needs before proceeding into the actual design process. For purposes of this thesis, it is taken as a given that competent authority has identified a need for a new vessel to execute the MIO mission, and that need has been duly validated and certified.

D. DESIGN APPROACHES CONSIDERED

1. Current Design Approaches

There challenge to improve the ship design process is no small one. The literature abounds with different approaches and variations of how to tackle this problem. Most appear to include at least some level of modeling. This section will review a few of them.

The Naval Sea Systems Command (NAVSEA) Surface Ship Design and Systems Engineering Directorate (05D) currently relies on a program called Leading Edge Architecting for Prototyping Systems, or LEAPS, in developing ship design. Developed cooperatively with the University of Michigan, LEAPS, as explained by Kassel, Cooper and MacKenna (2010), "is a very powerful software environment that includes a CAD and math engine and several useful tool kits." However, it still relies on ASSET, a Navy designed and owned Naval Architecture CAD program, which uses a traditional design spiral approach to ship design. By bringing in data from other software programs and synthesizing it, LEAPS aims to speed the processes up while enabling a more complete design model at the outset. It is also as much a process as it is a software package.

Famme, Gallagher, and Raith (2009) describe a process they call the *Performance-Based Design Continuum (PBDC)*, which is an enhancement of LEAPS. PBDC expands the process by further asserting that model specifications should become ship specifications, creating a broader model of more systems and sub-systems, and expanding the model beyond just the design phase into the building, testing, and life cycle support phases. The main purpose of developing PBDC was to further understand (and therefore reduce) total ownership cost. The authors assert that the process has in fact done that when used, and given its thoroughness, it is likely valid. However, it still places primary emphasis on *ship performance*, not combat performance in an operational environment.

In an alternative approach, there is much time devoted in current literature to Set-Based Design as applied to ship design principals (e.g., Singer, Doery, and Buckley (2009); Mebane et al. (2011), and McKenney, Kemink and Singer (2011)). At the most basic level, set-based design provides an approach to design, whereby an entire design space is laid out, and within that space are several sets of design areas (HM&E, combat systems, *et cetera*). Initially, those sets are defined as broadly as possible, and through various research methodologies, are brought in tighter and tighter as more and more overlap is found. In 2010, a Naval Sea Systems Command team pioneered a successful design of the LCAC replacement using a tailored set-based design approach (Mebane et al., 2011).

The main drawback to this approach, however, is that while it provides a very useful framework for visually conceptualizing the design process, it provides little in the way of concrete steps to execute the process. For example, as the name implies, there is a potential to explore the evolution of the design space using set theory, however literature exploring that appears to not exist. The approach used in this research is likely to be compatible with set-based design approaches as a conceptual framework, but it does not, *per se*, strictly follow them.

2. Capability-Based Analysis (CBA) Applied to Ship Design

Regardless of the approach used, there is a predominant movement that believes no matter how the process is executed, operational capability should always be at the forefront of all major design decisions. This is likely where the term "Capability-based analysis" derives from. There is however, no clear-cut definition of exactly what "Capability-Based Analysis" is. The Department of Defense Acquisition System uses the closely related "Capability-Based Assessment," or CBA to describe the formalized process of identifying required mission areas, current capabilities in those mission areas, and the gaps between those capabilities and requirements, but that does not specifically address the design process itself; only what is to be designed in operational terms.

For purposes of this thesis, the concept of Capability-Based Design, as applied to ship design, can trace at least some roots back to the work of Dean Rains (1984). His "Combatant Ship Design Guidance Through Mission Effectiveness Analysis" may have been among the very first published works to suggest that combat measures of effectiveness should be used to influence the design attributes of a ship. The next significant work in the field may be from William Hockberger in 1996. In his seminal work, "Total System Ship Design in a Supersystem Framework," he set a basic schema of viewing a single ship's value by what it contributes to the battle group (or at least next higher organization level) in which it is a part. Most prominently, he lays out the importance of understanding the difference between Measures of Performance (MOPs) vs. Measures of Effectiveness (MOEs), both in general and with respect to ship design. In a simplistic explanation, an MOP describes what a system does on an easily measurable scale (speed, firing rate, radar range, *et cetera*), while an MOE attempts to measure how a system performs in the external environment towards achieving a desired result (a kill ratio for example). He argues that successful ship design should stem from thorough and accurate MOEs, which can and should be determined before a Naval Architect ever sets pencil to drafting paper.

The broad discussion moves through how that has contributed to evolving the alternatives selection process for choosing between designs (Hootman 2005), but it does not necessarily inform the design of a hull. Recent lessons learned in ship design, such as LCS, point out resulting dramatic cost overruns, partially because requirements were not set (or evolved) throughout the design and construction process. In fact, from a 2004 OMB report on shipbuilding, "the average over-cost of new ship classes is 30% and the major reason is release to production of premature designs (Famme, Gallager, and Raitch, 2009)." It then follows that anything that can be done to determine and set requirements early in the process would be advantageous.

Several recent innovations have emerged to address this problem broadly centered on concepts of responses surface methodology, or RSM. RSM is, essentially, using computers to rapidly develop and produce multi-dimension mathematical meta-models and displaying them in two dimensions to examine the complex interactions between several design factors and responses to them. Psallidas, Whitcomb, and Hootman (2010a) used this approach to demonstrate a method of measuring how a submarine design consideration (specifically Air Independent Propulsion) could have theater-level impacts. The same authors (2010b) showed a method for modeling the impact of technology insertion in sub design. Letourneau (2009) used a RSM approach to show a method of setting top-level design criteria for an autonomous subsurface craft.

Choi (2009) applied multi-criteria objective decision-making methods to define an Overall Measure of Effectiveness (OMOE) score for a series of discrete ship designs, and then used RSM techniques to show trade-offs between the different MOEs and how they impacted the OMOE. However, the MOEs in that case were predominantly ship-design related, not operationally related (i.e., directly related to the combat system of the ship). Also applying RSM techniques, Gomez Torres (2010) explored operational modeling of small offshore patrol vessels across discrete mission areas with an eye towards ship design factors, and postulating how they might affect combatant performance. However this research did not show the links between the naval architecture elements of design and the combats systems elements of design.

In summary, the above research shows that RSM techniques are highly applicable to top-level ship design approaches. This research aims to further solidify the validity of the technique, as well as show how it can be used to related ship-design considerations that are meaningful to a naval architect to operational measures of effectiveness that are meaningful to a warfighter.

3. Total Ship System Engineering

The design approach this thesis takes first asserts that a combatant ship is fundamentally a system. Buede defines a System as "a collection of hardware, software, people, facilities, and procedures organized to accomplish some common objectives (2009)." Blanchard and Fabrycky initially state "a *system* is an assemblage of or combination of elements or parts forming a complex or unitary whole." However, they go on to clarify that

> [N]ot every set of items, facts, methods, or procedures is a system. A random group of items in a room would constitute a set with definite relationships between the items, but it would not qualify as a system because of the absence of unity, functional relationships, and useful purpose.

Finally, they state that the elements of system include components, attributes, and relationships.

From these definitions, it should be clear that a surface combatant is a system. It may be composed of hundreds—or perhaps even thousands—of subsystems, but they all interact to produce one single system, with one or more unitary objectives. From the author's personal experience, there is no one subsystem on a ship can function without at least one other, further solidifying the that a ship should be considered a system.

Given that to be true, then to take any approach to designing a combatant that ignores any major subsystem or component of design right from the very beginning would then be folly. That is to say, the ship must be engineered as a total system from the start. However, the crux of the matter lies is defining the initial design space, to borrow a concept from set-based design. Put another way, we must first answer, "What matters?"

Answering it is anything but easy. From the historical discussion above, the answer—one that was highly effective for decades—was retaining a core of extremely knowledgeable people that, over time, came to understand the design space. Unfortunately, that knowledge base has effectively been lost (Keane et al., 2010). The advantage that modern design does enjoy today has been the advent of super computer and the arrival of relatively simple and accessible design programs, which together can help to make up that time deficit with extraordinary computer power. However, that power alone is not enough to design a system as complex as a ship. There must also be considerable experience influencing the design (which can come from academic disciplines such as Operations Analysis (OA) and actual operational experience) coupled with a thorough understanding of the capabilities and limitations of the tools employed.

The method presented here seeks to do that. It starts with a capability-based approach to determine what is needed in a design. It then draws on the author's operational experience (as a surrogate for the team of experts that should begin the process of requirements setting) and research based in the Operations Analysis field to build an operational model that captures the subsystems that should influence the ship design.

E. METHOD

The Systems Engineer has a myriad of powerful tools at his or her disposal in designing any system. Broadly speaking, any tools used by the systems engineer tend to be used to define or refine the design space of a particular project, with the ultimate goal of aiding a decision maker in making a rational decision. It is the author's opinion that there is not one method that is a panacea for all design problems, but the use of multiple tools that complement each other may lead to better decisions. What follows is a brief description of the design tools used in this research.

1. Discrete Event Simulation

Discrete Event Simulation (DES) is a broad subset in the field of modeling and simulation. It models "a system as it evolves over time by a representation which the same variables change instantaneously at separate points in time...at which an event occurs… in which an event is an instantaneous occurrence that may change the state of the system" (Law, 2006). A key component of any DES is that it proceeds according to time, controlled by a simulation clock.

The elements within the model, typically called "entities," have attributes that define them. The modeling method essentially captures the state of all the attributes for the entities at each time and calculates what the state should be for those attributes at the next time step. Because of this, any needed data can be captured as it is needed as the system passes through its states. Since the time steps are discrete, they can be set to any step size, and "simulation time" simple runs as quickly as a computer can step through the calculations, and therefore an event that may occur over weeks can be modeled in minutes (Law, 2006)

A popular alternative to Discrete Event Simulation is Agent-Based Modeling (ABM), which is a type of "process approach" to modeling. Where a DES is strictly time-based, an agent-based model instead looks more at how autonomous agents in the model interact in a complex environment; how they "see" their role in the system. However, it should still be noted that the underlying code of this modeling approach still relies on time as a controlling factor (Law, 2006).

In a DES, the model will predict the state of all entities and make a determination if a certain event is to occur, and then update the entities accordingly. In an agent-based model, the emphasis would be on modeling the decision itself, where from a software perspective, two entities might make a "decision" to react based on a comparison between their own properties (Holland and Wallace). It is similar to the difference between the first and third person in story telling. In a DES, an omnipotent model controls the entire simulation, while an ABM focuses on the individual's perspective. To carry the analogy a bit further, in both cases you will get the same "story," but you will learn more about the individual players and less about the larger context in an ABM.

ABMs are generally better suited for complex systems where it is easier to observe individual behavior or "where empirical data is insufficient to provide statistical representations" (Holland and Wallace). The tradeoff, however, is that they are more computationally complex and more difficult to program (Law, 2006).

In this approach to systems engineering, an ABM approach would likely be better suited, especially since the intent is to observe how the individual ship behaves in the system, not necessarily how the system as a whole performs. However, in the case of the simple MIO mission in which there is empirical and statistical data readily available, DES should be a rational approach given time and costs constraints for this research.

2. Design of Experiments

Experimental design or the design of experiments (DOE) is a practice that has roots in the practical sciences and statistics. In the most general sense, it encompasses a process by which the impacts of inputs to a process (generally called "factors") have on an output (called the "response") which can be measured.

The primary goal of any experimental design should be to use the tool to make best use of scarce resource, whether this resource is time, computing power, material, *et cetera*. As such, it provides a structured approach to experimentation in which there are multiple factors that may interact in complex ways to produce one or more responses in a system. Perhaps more importantly, it aids in the identification of factors that are potentially less significant (or completely insignificant). Once those factors have been identified, the experimenter can then focus those limited resources and develop a more robust experiment that focuses on only the factors of primary interest.

The natural progression of the experimental design will often lead to the use of response surface methodology. Originally introduced by George P. Box and K. B. Wilson in 1951, it focused on modeling the relationships between factors and a response using second-degree polynomials to ultimately produce a multi-dimensional, continuous surface to predict how combinations of variables would impact the response of interest. Bearing in mind they would largely work the math by hand in the 1950s, the original methodology was limited. With modern software such as SAS JMP® and even a typical desktop computer's processing power, models of increasing complexity and fidelity are easily created, and can model many factors and responses.

The major drawback to response surface methodology, however, is that all the factors must be continuous. Unfortunately, that is not always the case when dealing with total ship design, and especially when considering the combat system design. In the latter case, there is a tendency to gravitate towards starting with existing systems rather than assuming a clean slate for a new system (and for good reason, mostly related to time and cost involved). Therefore, until continuous relationships can be developed (for example, how frequency, bandwidth, and antenna size relate to the physical size of a radar), this method will often be limited to traditional least squares regression analysis.

F. SCOPE OF THIS THESIS

This scope of this research is primarily to examine a potential process for combatant ship design using a relatively simple single-mission platform, namely the Maritime Interdiction Operation (MIO) mission set. The designed platform will only perform one primary mission. The models used in the process (specifically ExtendSIM™ and an Excel™-based ship design tool) are relatively straightforward and simple, and should be taken as a stand-in for the more complex modeling and simulation tools available. It will also look at only one portion of one mission. Finally, the result of this research will be a recommendation to follow (or not follow) a process, not the recommendation of a design for any particular type of ship.

G. BENEFITS OF THIS STUDY

This thesis will emphasize a process for ship design the breaks from a more traditional approach of basing a ship design on size constraints. It is meant to further thought and discussion of ways of seeing and designing a ship as a total system rather than the sum of the sub-systems. By illustrating a complex process using a relatively simple mission set in a narrowly defined Operational Situation (OPSIT), it is hoped that the groundwork that is already in place for this approach will be expanded. Eventually, it potentially be applied to more complex OPSITS, and for multi-mission platforms, as modern surface combatants have become.

II. DESIGN REFERENCE MISSION AND MEASURES OF EFFECTIVENESS

Skolnick and Wilson (2000) explain that the Design Reference Mission (DRM) evolved from the AEGIS approach to engineering an air defense system in the mid-1960s. It “defines the projected threat and operating environment baseline for a rigorous systems engineering process to help ensure that future systems can meet [future] challenges and uncertainties.” Most importantly, it seeks to “define the problem, not the solution.” There is no set form for a DRM, but they argue it should at least include such considerations as the operational situation (OPSIT), threat characterization and tactics, the physical environment, and a timeline.

A. INTRODUCTION TO MARITIME INTERCEPTION OPERATIONS (MIO)

Maritime Interception Operations, or MIO, in the broadest sense are the seaborne operations concerned with preventing illicit activity (such as smuggling) on the open ocean. As specifically defined in Joint Publication 1-02 (DoD Dictionary of Military and Associated Terms), MIO is the “efforts to monitor, query, and board merchant vessels in international waters to enforce sanctions against other nations such as those in support of United Nations Security Council Resolutions and/or prevent the transport of restricted goods.”

In a practical sense, there are two main sub-sets of this mission currently for the U.S. Navy. One is the enforcement of UN sanctions on the Gulf States, and the other focuses on counter-drug operations. This thesis focuses on the former, largely as that is the basis of the professional experience of the author.

As with most if not all mission sets, the MIO mission can be broken into phases. Generally, they are search, intercept, board, and if necessary, escort. As will be seen , the majority of the Measures of Effectiveness developed for this mission set are focused on the latter two phases, particularly the boarding. The boarding phase is almost completely independent of the ship design, so long as there is a sufficient amount of room for the boarding team to live and store a relatively small amount of gear, and there is a built-in ability to communicate with higher headquarters. The first two phases, however, are directly tied to the design of the ship, and although effectively only one MOE is tied to them—the probability of intercept—the remaining measures are tied to the successful detection and interception of the target to begin with.

The detection and interception of a target vessel is, by comparison, a simple mission, especially when viewed against other missions such as anti submarine warfare. Because of its simplicity, it makes it an ideal choice to use in the demonstration of a process. In other words, the point of this research is not to design a ship, but to show a method by which a ship can be designed using a simple example.

To execute this mission, this simple vessel must be able to do two things. First, it has to find the target vessel. Then it has to catch it. To a lesser extent, it must also be able to stay on station long enough to search for extended periods and escort suspect vessels when necessary. Modern technology has rendered the search and detection problem much easier, such as with the use of the Automated Identification System, satellite imagery, intelligence, and so on. All of these technologies may be easy to independently model, but showing how they interact is a challenge of substantial magnitude. Therefore, this vessel will simply rely on tried-and-true radar. The intercept portion is also relatively easy. Given enough speed (a function of the hull design) and enough time (a function of the effectiveness of the radar), virtually any intercept is feasible.

B. OPERATIONAL SITUATION (OPSIT)

A mission set, a "5th Fleet" (Middle East) *fictional* scenario, was selected to illustrate the method. It is sometime in the not-too-distant future. The United Nations has placed sanctions on many goods flowing into Iran. Intelligence has identified that these goods are moving overland to the remote and largely uninhabited north eastern coastal region on the western shore, and then moving across the Persian Gulf in small dhows, indistinguishable from any of the traditional fishing vessels typical of the area (see Figure 1).

Figure 1 A typical Arabian Gulf Dhow (photo by A. Davey, from http://thegulfoilspill.org/dhow-on-dubai-creek/).

The Combatant Commander (COCOM) has determined the best way to stop these goods is to do so while they are in international waters at sea. The COCOM tasks his Maritime Component Commander (MCC) to stop the flow of these sanctioned goods into Iran. The MCC turns to this new class Offshore Patrol and MIO vessels to get the job done.

The operational planners learned that neutral countries have grown unfriendly to these vessels moving through their own territorial waters, and that has forced the smugglers to attempt to make a “run for it” across the Gulf into a major port on the western shore. They have subsequently identified a 110 by 55 nautical mile box that they believe contains the bulk of the illicit traffic. They have determined that a barrier patrol setting up a comfortable distance (about 10 nautical miles) outside territorial waters of the destination country would stand the best chance of detecting and intercepting targets of interest.

The smugglers are using classic wooden dhows, roughly 3 meters high at the main deck by 50 meters long. They are capable of moving at an average top speed of 7 knots. Intelligence indicates that they are attempting to run the gulf on average every 1.2 days. They will generally parallel the long axis of the box, but they may use oblique angles in an attempt to blend in better with local fishing patterns.

The Gulf environment is generally a hostile one to most systems. Temperatures typically soar of 100°F in the summer months. Frequent sand storms blow across the water, causing limited visibility and increase radar attenuation. However, it is equally likely to be a calm, clear, and still day.

C. MEASURES OF PERFORMANCE AND EFFECTIVENESS

The Systems Engineering process should use a "solution neutral" approach. However, for purposes of this paper, some assumptions about what has already happened in that process must be made to arrive at a ship for a solution. First, the requirements office within the Office of the Chief of Naval Operations has identified and validated a need to address the issue in the DRM. Current capabilities were analyzed and a gap in those capabilities was identified. A broad range of potential solutions were considered, all of which can be classified by as a component of DOTMLPF (doctrine, operations, training, materiel, leadership, personnel, and facilities). Decision makers determined a materiel solution was the correct way to close the gap. Material solutions were considered across the broad spectrum of Naval Capabilities, to include air assets, sub-surface assets, special forces, and surface assets. A rational decision making process was followed, and it was determined that a new surface ship of some variety was required to close the gap.

Now that a specific materiel solution has been identified, the design team can begin to take on the challenge. The first questions that they should ask are "What tasks need to be accomplished to achieve a successful mission?" and "How is the effectiveness of this solution going to be measured?" MIO is an existing mission set, so the designers turn to the Measures of Effectiveness in the Uniform Joint Task List (UJTL) to find their answer. However, these should also be same measures that were used to identify the correct type of solution. Table 1 shows the MOEs task in the MIO Task.

There are a couple of initial key points from this list. First, there is little on here that would directly impact the design of the ship, so long as it had room for a crew to conduct boardings and house refugees. While relevant, these types of considerations do not become important until the internal layout of the ship is determined. Second, in order to calculate most of these MOEs, something must be known of the enemy's actions that are completely independent of the ship design (for example, one must know how much contraband was flowing to a target country before the percentage reduction can be calculated).

Table 1 UTJL MOEs for the MIO Task OP 1.4.4. (From UJTL)

MOE Number	**Units**	**Measure**
M1	Percent	Of pre-action smuggling maintained.
M2	Percent	Of vessels boarded.
M3	Percent	Of vessels diverted had contraband.
M4	Percent	Reduction in flow of contraband to (or from) target nation.
M5	Percent	Reduction in flow of refugees to (or from) target nation.
M6	Refugees	Diverted Daily to receiving station.
M7	Refugees	Found on vessels.
M8	Hours	To process and divert refugees to receiving stations.
M9	Vessels	Boarded.
M10	Vessels	Diverted due to (suspected) contraband.
M11	Percent	Of pre-action smuggling maintained through alternative routes.

Finding good information, yet not enough to aid in the design of a ship (not too surprising since this is a JOINT task list), the designers may next proceed to the Unified Naval Task List (UNTL). It has a similar list for both Naval and Marine Forces, and the Naval list is reproduced in Table 2 (note that in Table 2, the inconsistency between "interception" and "interdiction" is carried from the original. There is no effective difference between the terms). Unfortunately, the UNTL does not provide a clear answer, either, but it does allow some solid inferences. First, in order to achieve most of those MOEs, the target vessels must be found (detected). Second, in order to board them, they must be intercepted. These inferences are supported by the accompanying text for each task, although not reproduced here. These inferences can be reduced to one key measure of effectiveness that must be achieved before any of the others can occur: the probability of intercepting a suspected vessel, or P(I). It is important to note here that in keeping with Hockberger's assertion and formalized by INCOSE's Technical Performance Measurement Guide (2005) as to what an MOE should be, P(I) is an external measure that is of interest to the "customer" (the COCOM in this case). This is because if P(I) is anything less than 1, the practical meaning is that at least one suspect vessel escaped, and the overall mission objectives (from the commander's perspective) have not being achieved (vis-à-vis *stopping* the flow of contraband, *et cetera*).

The next design step would be to break the interception itself down into sub-tasks or functions, much as the UNTL does. In order to consummate an interception, the patrol vessel must search for a target, detect it, classify, and intercept it. After the interception occurs, the boarding would happen. The designers would then need to seek systems that could accomplish those tasks, and then map those systems to those functions to ensure all functions are covered. Again assuming that process is complete, those systems could include a radar and the maneuverability of the ship. Table 3 shows how those systems match to those functions in what is generally known in the DoD as a traceability matrix.

Table 2 MOEs for the MIO Task and some sub-tasks, NTA 1.4.6. (From UNTL)

NTA 1.4.6: Conduct Maritime Interception		
M1	Lb.	Of contraband confiscated or destroyed per week.
M2	Percent	Of targeted forces interdicted.
M3	Percent	Reduction in flow of all supplies to (or from) a targeted nation
NTA 1.4.6.1: Conduct Visit		
M1	Hours	Between directing vessel to heave to and placing boarding team aboard.
M2	Percent	Of vessels complying with order to heave to.
M3	Percent	Of vessels with valid documentation.
NTA 1.4.6.4: Escort Detained Vessel		
M1	Hours	Time vessel is under escort by friendly forces.
M2	Number	Of vessel crew in poor health or suffering injury.
M3	Hours	Friendly forces are taken off station due to escort.

Table 3 A possible system traceability matrix for the notional patrol vessel.

	Functions				
System	Search	Detect	Classify	Intercept	Board
Radar	X	X	X		
Maneuver	X			X	
Endurance	X			X	X

The next series of steps would be to create measures of performance (MOPs) that can be traced to functions. For example, in order for the radar to detect something, it must have a reasonable range with a high probability of detection. That would lead to the first MOP, radar range, a measure that is internal to the ship. Now the designer must understand what dictates radar range. While there are many factors, the two predominant (or potentially limiting) ones from (Harney, 2010) are height of the antenna and the characteristics of the radar itself (frequency, aperture size, *et cetera*). The designer should account for these two design considerations to estimate the MOP of radar range, which becomes one of the components in estimating the MOE, probability of interception.

The same logic can be applied to the maneuverability function. After stepping though that, it can be shown that the designer should be concerned with the search speed and the intercept speed, which are two other MOPs that may have a bearing on P(I). Lastly, from the UJTL and UNTL it should be apparent that time is a consideration in the MIO mission. Specifically, the vessel appears to need a capability to remain on station for some time, both to prolong its ability to search longer and to conduct boardings and escorts.

D. CHAPTER SUMMARY

This chapter introduced the concept of the design reference mission (DRM) and constructed one for use in this paper. After providing an overview of the MIO mission, it presented the OPSIT for this paper. The OPSIT selected is based on a future counter-smuggling/UN Embargo operation against target dhows in the Persian Gulf.

The following section highlighted the process measures of effectiveness (MOEs) might be generated, and then showed that the likely best MOE for this design is probability of interception, or P(I). It then proceeded to show how the MOE could be broken down into functions and measures of performance, which were then tied to key design characteristics that, if they are properly traced, can predict a measure of effectiveness in the design space.

III. OPERATIONAL MODEL

A. MODEL DEVELOPMENT AND IMPLEMENTATION

The first component of this process is to develop a model to represent the mission under examination. The primary objective of any operational model should using this approach should be to emphasize the features of the system being designed that are going to influence the design. This was completed in the previous chapter. The essential step here is to identify early on what physical characteristics drive the operational performance.

The MIO mission provides a simple example of how to approach this problem. As identified in the previous chapter, the main measure of effectiveness (from the Universal Joint and Naval Task Lists) that is going to impact ship design is its probability of intercept. Through a traceable hierarchy, it was shown that in order to achieve that intercept, the patrol vessel must search for the target, detect it, classify it, and intercept it.

Recall from the Design Reference Mission, that the patrol vessel is going to conduct a barrier patrol. Turning to the discipline of Operations Analysis, it can be shown that the best way to conduct a barrier patrol when the search vessel has a relatively small speed advantage over the target vessel, either a linear or crossover barrier patrol may be employed. The patrol method to employ is a function of the size and area to be searched, relative speed of the two vessels, and the sweep width of the searching radar. Since we know that sweep width is a variable based on radar performance, we first note that our design choice may have an impact on tactics which in turn are likely to have an impact on operational performance, we note that this may need to be modeled. Since relative speed is also a consideration, we note, too that this should likely be modeled.

In the operational analysis context and as used in the search equations, radar sweep width is essentially the range of the radar in which there is a probability of detection of near one. When estimating this potential range, there are two factors that are predominant. First is the height of the antenna and height of target, which together determine the radar horizon. Second is the actual performance of the radar itself, which can be estimated using a basic radar range equation (Harney). From a ship design perspective, these two factors are both going to figure into that ship's design. The weight of the radar system and the height above baseline of the antenna are going to impact stability calculations and will consume a portion of the displacement allotted for the payload (Gillmer and Johnson, 1982).

Once the ship is detected, the target must be intercepted. Tactics play a major part in this, as a relatively disadvantageous position can be overcome by superior speed of the intercepting vessel. Likewise, a wise tactical position can overcome a relative lack intercept speed. However, intercept speed will play a part in ship design, so it should be considered.

Finally, the patrol vessel's on-station time may impact its potential success. The longer it can be on station patrolling, the greater the potential for intercepting target vessels. The on-station or endurance time is also going to influence (or be influenced by) the amount of fuel the patrol vessel can carry, the rate at that it burns, *et cetera*.

Following the above discussion, Table 4 summarizes the potential design factors that were determined which should be modeled in the operational model.

Table 4 Model factors and projected impacts on operational capability and ship design.

Design Factor	Potential Operational Impact	Potential Ship Design Impact
Radar Height	Size of sweep width, greater P(D)	Stability
Radar Type	Size of Sweep Width, greater P(D)	Stability, payload margin impact
Search Speed	Search area per unit time, impact on P(D)	Required fuel on board, hull design considerations
Intercept Speed	Direct impact on P(I)	Required fuel on board, hull design considerations
Endurance	Possible impact on P(D)	Required fuel on board

Now that the factors that should be modeled are determined, the next step is to develop a simulation approach that can capture those inputs and outputs. Figure 2 illustrates the flow of logic that guided the simulation development. This model development was influenced by the work of Hiroyuki Sato (2005). Although his work concerned maritime patrol aircraft in the MIO mission and was pure Operations Research, his approach to a similar operational challenge was relevant to this model.

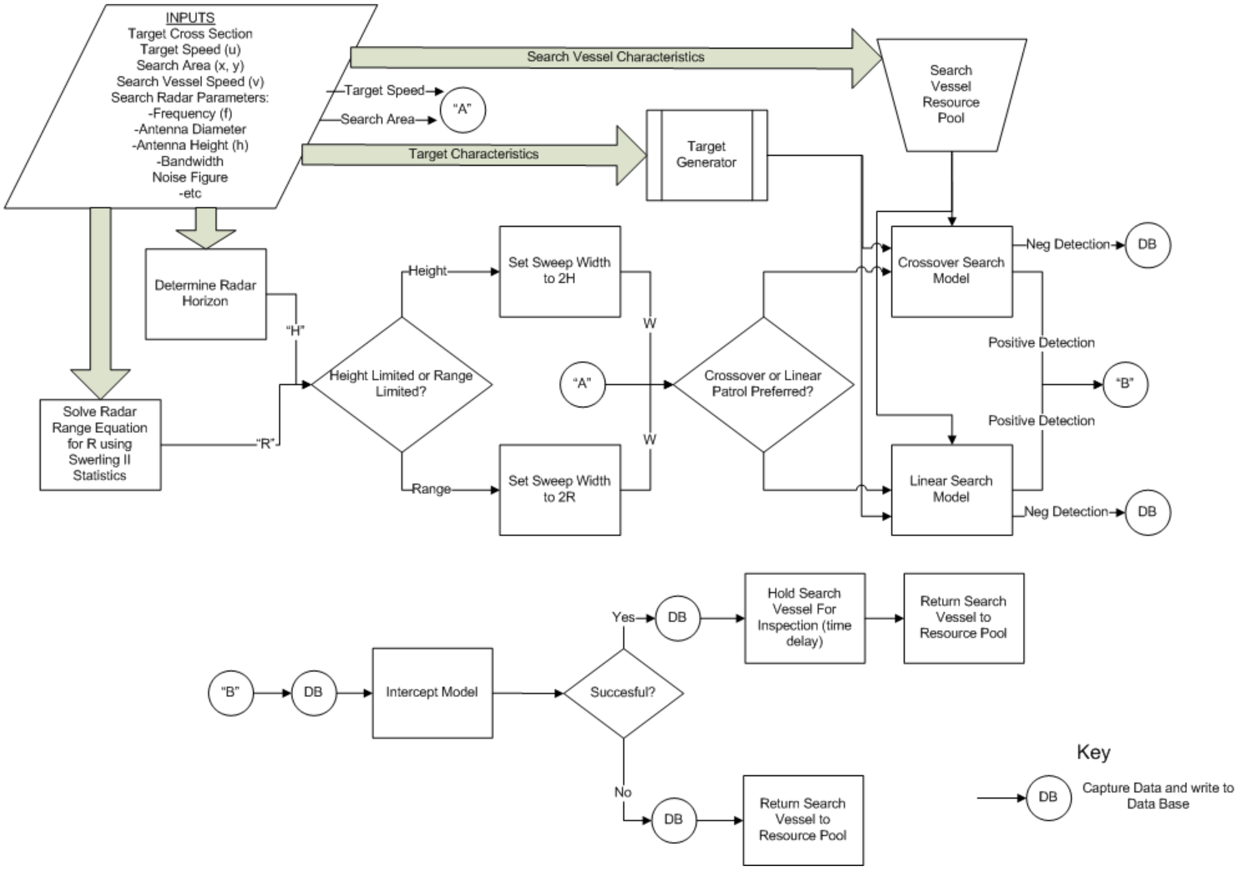


Figure 2 Logic flow model for the operational simulation.

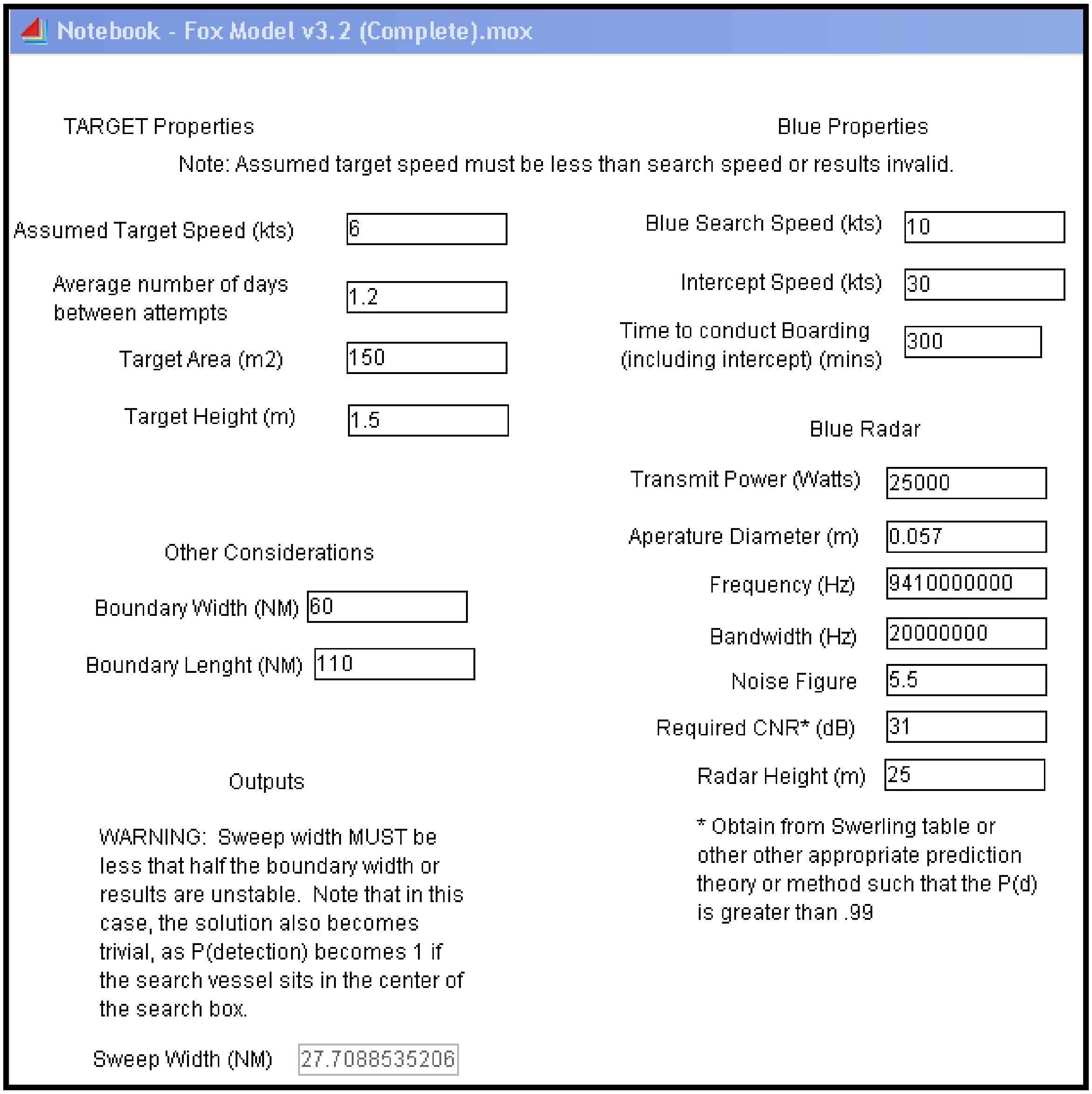
Inputs can be classified by who is responsible for their input. First are the operational inputs that stem from the Design Reference Mission. These inputs, such as target type and frequency, and search area would come from intelligence estimates or an operations analysis team. The remaining inputs come from the design team, and relate specifically to the characteristics of the search vessel. In this construct, the author envisions both teams working simultaneously to develop the most realistic scenario.

On execution, several initial pre-simulation steps occur. First, the predicted radar range is calculated, based on antenna height and radar characteristics. Then the sweep width is set to twice the lesser of the values. The next step is the determination of the search type—linear or crossover. This is a function of the relative patrol vessel and target speeds and the search area. Appendix A documents the underlying math in these decision processes.

Next, a series of target vessels and a single patrol vessel are generated. The target enters the simulated search area while the patrol vessel patrols. If the distance between the two vessels should ever be less than the sweep width, a detection is counted, and the model moves to the intercept phase. An intercept is deemed successful if the patrol vessel can get to the edge of the box before the target vessel can. Note that this is a conservative means of determining a potential intercept. In reality, the patrol vessel will generate an optimum intercept course. However, the computations required to simulate this are complex and it is likely they will unduly slow the simulation down, so the more conservative means of estimating this—predicting who "gets to the finish line first"—is used as a surrogate to capture this information. If the vessel is successfully intercepted, it is boarded. After the boarding, the patrol vessel returns to station to search for the next target (the escorting process in the event of a diverted vessel is not modeled).

The circles with "DB" in them represent the points in the simulation where data is collected. If a target vessel passes through the area without being detected, it is counted as having "evaded." If it is detected but cannot be intercepted, it is classified as having "escaped." Otherwise, it is classified as "intercepted." There is one additional data point not shown where the total number of targets that were generated for each simulation is captured.

From the logic flow model that was just described, the operational model itself was constructed using the ExtendSim software suite. Screenshots of the final model as built in ExtendSim can be found in Appendix B. Figure 3 is a screen shot of the notebook where all inputs except endurance are entered (endurance is entered directly in the Run Setup screen by adjusting the length of the trial) from the final model.



Notebook - Fox Model v3.2 (Complete).mox

TARGET Properties

Blue Properties

Note: Assumed target speed must be less than search speed or results invalid.

Assumed Target Speed (kts) 6

Average number of days between attempts 1.2

Target Area (m2) 150

Target Height (m) 1.5

Blue Search Speed (kts) 10

Intercept Speed (kts) 30

Time to conduct Boarding (including intercept) (mins) 300

Blue Radar

Transmit Power (Watts) 25000

Aperature Diameter (m) 0.057

Frequency (Hz) 9410000000

Bandwidth (Hz) 20000000

Noise Figure 5.5

Required CNR* (dB) 31

Radar Height (m) 25

* Obtain from Swerling table or other other appropriate prediction theory or method such that the P(d) is greater than .99

Other Considerations

Boundary Width (NM) 60

Boundary Lenght (NM) 110

Outputs

WARNING: Sweep width MUST be less that half the boundary width or results are unstable. Note that in this case, the solution also becomes trivial, as P(detection) becomes 1 if the search vessel sits in the center of the search box.

Sweep Width (NM) 27.7088535206

Figure 3 Screen shot of ExtendSim notebook where model factors are input.

B. FACTORS, EXPERIMENTAL DESIGN, AND RESPONSES

Recall that there are five design characteristics to model: radar type, radar height, search speed, intercept speed, and endurance. Table 5 shows the Five-factor, multi-level DOE that was used to evaluate the operational model, followed by a description of how the values were assigned.

Table 5 Factors and levels for DOE.

		Levels		
Factors	**Type**	Level 1	Level 2	Level 3
Radar Height (m)	Continuous	15	20	25
Radar Type	Categorical	Low-End	Mid-Grade	High End
Search Speed (knots)	Continuous	10	15	20
Intercept Speed	Continuous	20	25	30
Endurance (days)	Categorical	7	14	N/A

Radar antenna height, search speed, and intercept speeds capture the range of typical values of surface combatants. The two levels of endurance, representing the time that the patrol vessel would spend conducting the barrier patrol before returning to base for resupply, represent a shorter and longer possible, but reasonable, time a vessel of that size (or more specifically, her crew) could be expected to stay on station. The radar types are meant to represent, respectively:

- A high-end commercial off-the-shelf surface search radar
- A standard military grade surface search/navigation radar
- A Surface fire control radar

Appendix C presents the parameters used to model each of the three types of radars.

A Full factorial design results in 162 runs for this particular 5 factor, multi-level design. If each simulation is run for 1,000 repetitions, each run would take between one and two hours. Therefore, a screening experiment was designed using SAS JMP® software. The software was permitted to select the method, and a Taguchi L18 approach was used. Table 6 presents the resulting matrix.

Table 6 Taguchi L18 DOE trials for operational model.

Run	Endurance	Radar Type	Radar Height	Search Speed	Intercept Speed
1	7	L	15	20	20
2	7	M	25	20	20
3	7	H	25	10	20
4	7	H	15	10	20
5	14	L	15	10	20
6	14	M	15	10	30
7	14	H	15	20	30
8	14	M	25	20	20
9	7	L	25	20	30
10	14	L	25	10	20
11	7	H	15	10	20
12	14	L	25	10	30
13	14	H	25	20	30
14	14	M	15	20	20
15	7	M	25	10	30
16	7	M	15	10	30
17	14	H	25	20	30
18	7	L	15	20	30

To further reduce the time required to complete the full experiment, two identical trials, one with 100 repetitions and one 1,000, were conducted. The mean of the smaller set of was compared against the mean of the larger set of repetitions. An unpaired, two-tail t-test and a two-tailed Z-test was conducted to test the difference in means, and no significant difference was found. Therefore, for all trials, only 100 repetitions were conducted in the interest of time, as this study is only meant to show a process, not a final product. The author would recommend at least 1,000 repetitions if designing an actual system.

Sweep width (as a function of radar range or antenna height, vessel speeds, and endurance are Measures of Performance (MOPs); they are relatively easy to measure in the physical world, so they are the key factors that are modeled here. This concept is key to the traditional Systems Engineering Vee model. Assuming these MOPs are validated in this or any model, *they should be the same MOPs used in the verification process of the physical ship.*

Recall now the discussion in the previous chapter concerning the MOE of interest, P(I), and how the MOPs can be shown to ultimately predict the MOE. There is no inherent way to measure how these MOPs can predict the MOE in the real world, however the power of simulation allows us to measure the outcome—or response—and then estimate the relationship of the MOPs to the MOEs.

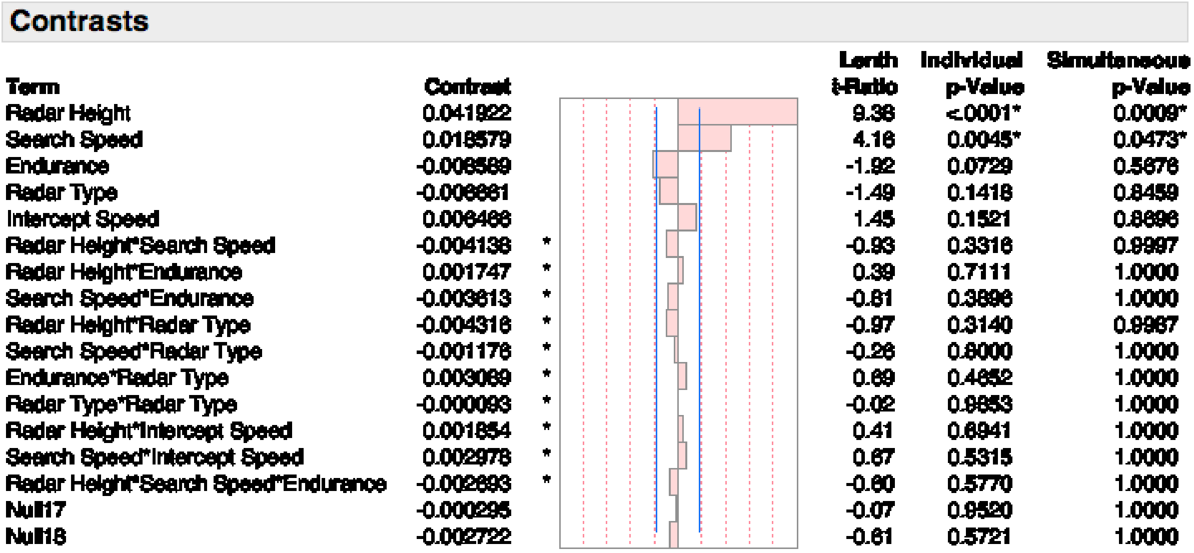
The model captures some key data that is used to measure the P(I). It is simply the ratio of the total targets intercepted over the total targets created. Both of these numbers are captured directly into a JMP database and then moved to a Microsoft Excel spreadsheet for computation. The P(I) was calculated for each repetition. The P(I) for each trial is the mean of all 100 repetitions.

Some additional potential measures of effectiveness were also considered. The probability of detection [P(D)] was easily captured, so it was measured in a similar way to P(I). It is important to note here that in this case, P(D) does not refer specifically to the radar's probability of detection. It would be more correct to say that it is the probability of a target vessel being detected by the patrol vessel. Also, the probability of intercept given a detection, or P(I|D) was easily calculated by dividing the number of intercepts by the number of detections for each repletion.

Upon inspection, the latter two candidate responses were rejected. P(I|D) showed almost no variance and was practically equal to 1. The likely reason for this is the strategy employed: the barrier patrol was set up at the end of the run, giving the patrol vessel maximum opportunity to detect with the greater range to conduct the interception.

C. RESULTS

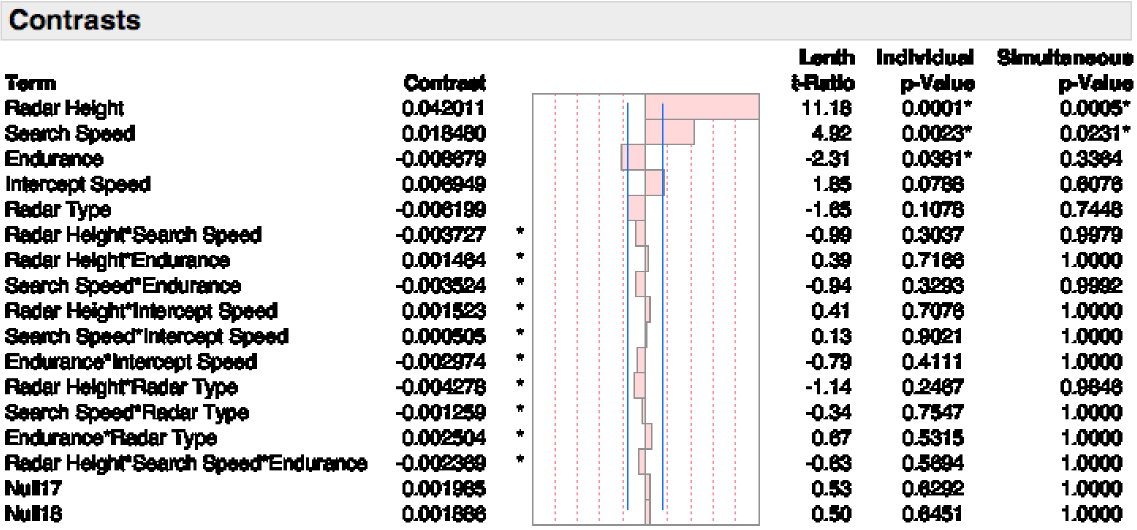
Figure 4 and Figure 5 present the contrasts for the screening experiments with P(D) and P(I) as produced by JMP, respectively.



Contrasts

Term	Contrast		Lenth t-Ratio	Individual p-Value	Simultaneous p-Value
Radar Height	0.041922		9.36	<.0001*	0.0009*
Search Speed	0.018579		4.16	0.0045*	0.0473*
Endurance	-0.008589		-1.92	0.0729	0.5676
Radar Type	-0.006661		-1.49	0.1418	0.8459
Intercept Speed	0.006466		1.45	0.1521	0.8696
Radar Height*Search Speed	-0.004138	*	-0.93	0.3316	0.9997
Radar Height*Endurance	0.001747	*	0.39	0.7111	1.0000
Search Speed*Endurance	-0.003613	*	-0.81	0.3896	1.0000
Radar Height*Radar Type	-0.004316	*	-0.97	0.3140	0.9987
Search Speed*Radar Type	-0.001176	*	-0.26	0.8000	1.0000
Endurance*Radar Type	0.003069	*	0.69	0.4652	1.0000
Radar Type*Radar Type	-0.000093	*	-0.02	0.9853	1.0000
Radar Height*Intercept Speed	0.001854	*	0.41	0.6941	1.0000
Search Speed*Intercept Speed	0.002978	*	0.67	0.5315	1.0000
Radar Height*Search Speed*Endurance	-0.002693	*	-0.60	0.5770	1.0000
Null17	-0.000295		-0.07	0.9520	1.0000
Null18	-0.002722		-0.61	0.5721	1.0000

Figure 4 Contrasts for screening experiment with P(D) as the response.



Contrasts

Term	Contrast		Lenth t-Ratio	Individual p-Value	Simultaneous p-Value
Radar Height	0.042011		11.18	0.0001*	0.0005*
Search Speed	0.018480		4.92	0.0023*	0.0231*
Endurance	-0.008679		-2.31	0.0381*	0.3364
Intercept Speed	0.006949		1.85	0.0788	0.6076
Radar Type	-0.006199		-1.65	0.1078	0.7448
Radar Height*Search Speed	-0.003727	*	-0.99	0.3037	0.9979
Radar Height*Endurance	0.001464	*	0.39	0.7166	1.0000
Search Speed*Endurance	-0.003524	*	-0.94	0.3293	0.9992
Radar Height*Intercept Speed	0.001523	*	0.41	0.7076	1.0000
Search Speed*Intercept Speed	0.000505	*	0.13	0.9021	1.0000
Endurance*Intercept Speed	-0.002974	*	-0.79	0.4111	1.0000
Radar Height*Radar Type	-0.004278	*	-1.14	0.2467	0.9846
Search Speed*Radar Type	-0.001259	*	-0.34	0.7547	1.0000
Endurance*Radar Type	0.002504	*	0.67	0.5315	1.0000
Radar Height*Search Speed*Endurance	-0.002369	*	-0.63	0.5694	1.0000
Null17	0.001985		0.53	0.6292	1.0000
Null18	0.001886		0.50	0.6451	1.0000

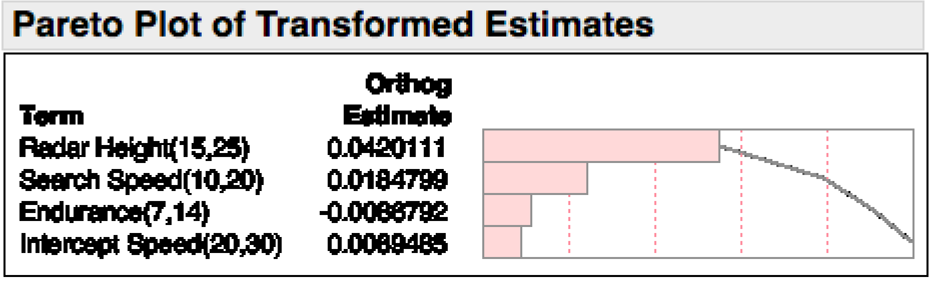
Figure 5 Contrasts for screening experiment with P(I) as the response.

With both P(D) and P(I) as the response, it is clear that radar antenna height and search speed are statistically significant ($p < 0.05$) for both responses. The endurance was the next heaviest weighting in each model, however it is only statistically significant in the P(I) model. No other terms were found to be statistically significant in this model. This is not very surprising, as a basic inspection of the data shows the for all but two of the trials, P(I|D) was 1, and it was nearly 1 in the two remaining ones.

The next step was to produce a model based on one of the responses. The probability of intercept was selected as the most appropriate response. With the P(I|D) near one, it could have been selected as well. However, the P(I) more closely matches the MOE from the UNTL. Based on the factors that were statistically significant, radar height, search speed, and endurance terms were included in the model. The resulting estimate of the relationship between those factors and P(I) is

$$P(I) = 0.443 + 0.041\left(\frac{\text{Radar Height} - 20}{5}\right) + 0.19\left(\frac{\text{Search Speed} - 15}{5}\right) - 0.009\left(\frac{\text{Endurance} - 10.5}{3.5}\right) + 0.007\left(\frac{\text{Intercept Spd.} - 25}{5}\right) + \varepsilon \tag{III-1}$$

The R-Square for the model fit for P(I) is .9055 with an adjusted R-Square of 0.8394 which indicates a reasonably good fit. Figure 6 depicts A Pareto Plot of these factors, highlighting their weight relative to each other. This expression and its relation to ship design will be discussed in detail in Chapter V.



Pareto Plot of Transformed Estimates

Term	Orthog Estimate
Radar Height(15,25)	0.0420111
Search Speed(10,20)	0.0184799
Endurance(7,14)	-0.0086792
Intercept Speed(20,30)	0.0069485

Figure 6 Pareto plot of factors in Operational model with P(I) as the response.

1. A Note On Radar Performance and Model Fidelity

The U.S. Office of Naval Research (ONR) and Italy’s Orizzonte Sistemi Navali in Rome jointly hosted a workshop in Rome in December of 2010 concerning the broad area of the subject of this thesis. Part of the discussion at the workshop centered on the fidelity required of the operational models, and specifically “how much is enough.”

While not a specific research goal of this thesis, an interesting and unexpected data point emerged on that issue that is relevant to the larger topic of total ship engineering and is, therefore, mentioned here.

In all trials, the radar range was limited by the height of the antenna. On the surface, this data would seem to suggest that radar antenna height is a suitable surrogate for range performance. However, this does not mesh with the author's personal experience in the Arabian Gulf, in which countless small dhows of the size in consideration would be detected visually long before they were recognizable as anything but clutter on even the "best" of the ship's radars except on the clearest, calmest of days.

In this particular model, recall attenuation and loss effects were neglected to both simplify the equation and make a closed-form solution for range possible. In reality, this is not the case, as attenuation is notoriously high and can be quite variable in the region. So while the data from this model may suggest that antenna height is a suitable surrogate, the author contends that in reality a higher-fidelity model of just the radar performance that includes realistic, stochastic modeling of attenuation factors (i.e. weather) is required before that question can be fundamentally or properly addressed.

D. CHAPTER SUMMARY

The MIO mission was first expressed with a logical flow diagram of how the mission would be executed based on MOP designed to measure a MOE. Design considerations that would impact those MOPs were identified and a DOE was developed to experimentally capture those results using a standard screening method. Once the significant factors were identified, a suitable linear mathematical model was created to express the relationships between three key design factors and the MOE, in this case probability of intercepting a target vessel.

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IV. SHIP DESIGN SYNTHESIS MODEL

To say that the design of a ship—the realm of the Naval Architect—is amazingly complex is a drastic understatement. Philipp Wolff (2000) somewhat glibly states that it is "because ships are the biggest moving objects man has ever made," but then goes on to postulate that it has more to do with the length of time that the ship is expected to last, coupled with the timing and sequence of design decisions. Further, one must merely glance at the size of Harold Saunder's seminal work, *Hydrodynamics in Ship Design*, to get a sense of the enormity of the science of the problem. Meanwhile, the graceful lines of well-designed ship simultaneously speak volumes to the artist's eye that the Naval Architect must also have. The author has found that the "perfect" computer-aided design (CAD) program or "ship design synthesis model" for the use in ship design is something of a "Holy Grail" for the naval architecture community. There are many available, ranging from online freeware, such as "FREE!ship" to more complex programs such as ASSET in use by the U.S. Navy, with countless approaches in between.

A. EXCEL MODEL

It is important to emphasize here that this work is not meant to be a treatise on Naval Architecture or to propose a specific ship design for a specific mission. And while it is based loosely on Saunder's preliminary steps in ship design, the design factors chosen for consideration are certainly not the only ones that could have been used, but were logically selected based on the type of ship being designed.

The ship synthesis model used to evaluate the responses in a standard ship design is a spreadsheet built by Clifford Whitcomb and Jim Moran, then at the Massachusetts Institute of Technology, and provided by Dr. Whitcomb. It was developed primarily as a cost-estimating tool to be used by students. The underlying ship design calculations and estimates are based on those used by ASSET. The power-estimating calculations derive from the work of K.U. Hollenbach. The cost estimating approach draws on the MIT

Math Model, and is primarily a weight-based approach. Further, it primarily synthesizes a medium to large surface combatant (approximately 4,000-10,000 tons) and assumes a displacement hull form.

The strength in this model is in its simplicity and ease of use. It will not produce a table of offsets to design a ship, but it does capture the major relationships between sub-systems and displacement, stability, and cost, for example. In essence, it is primarily meant to be a learning tool—a very good and reasonably accurate one—but still just a learning tool.

B. BASELINE SHIP AND MODEL INPUTS

As alluded to above, this model could begin almost anywhere. However as the intent of this research is to show the relationship between the ship design and the measures of effectiveness achieved by a notional combat system, it is most logical to begin with the same factors that were used previously to design the combat system. In a practical sense, this means showing how the vessel's endurance, search speed, radar type, antenna height, and intercept (max) speed influence the ship's design. The ship design responses will be discussed later.

Before that can begin, however, a baseline ship must be built. For the purpose of discussion here, a starting point must first be chosen, as a baseline ship cannot be built unless there is at least some concept of what it is to do. Since this is a single-mission ship, designed to patrol the relatively shallow waters of the gulf and carry a small crew, some type of offshore patrol vessel seems the natural choice. Although not a single-mission ship, the Róisín class of patrol vessels in the Irish Navy, Figure 7 Her principal dimensions are shown in Table 7.

Taking that as a starting point, the baseline ship was built by first imputing the above design factors at their respective mid points and holding them constant. The Combat System includes a surface search radar, a deck gun and other small arms, and other essential items for the safe operation of the ship (gyrocompass, IFF, *et cetera*). Then, using a ship of roughly 275 feet in length, a prismatic coefficient (C_P), Displacement Length Coefficient, and Maximum Section Coefficient (C_X) were selected.

Next, it is assumed that there will be two decks, 8 feet each, below the main deck, plus 2 and ½ feet of bilge fuel tanks, giving a Depth at Station 10 of 18 ½ feet. The ship was given a notional combat system of an OTO Malara gun and small arms, similar to the armament of the Róisín.

Figure 7 Róisín Class Patrol Vessel of the Irish Navy, a typical 1,500 tonne class vessel. (From www.janes.com).

Table 7 Principal characteristics of the Róisín Class Patrol Vessel. (After www.janes.com)

Principal Characteristics		
LWL	258.9	Ft
Beam	45.9	Ft
Draft	12.8	Ft
Δ	1727	Ltons
Sustained Speed	23.0	knt
Endurance Speed	15.0	knt
Endurance	6000	nm
Number Main Engines	2	
Main Engine Rating	6800	hp

The propulsion plant could easily be varied here, and the Naval Architect would likely look at required power and consider the type and number of engines needed as part of the initial trade space. The engine selection alone can have a very significant impact on the ship, especially if endurance is concerned (for example, if the amount of fuel carried is held constant and the efficiency of the propulsion plant is improved, for example, the endurance of the vessel will increase). Given that, a starting assumption must be made, and for that, two LM2500 gas turbine engines, each driving one shaft, will propel this ship. From these basic assumptions, a ship was designed and balanced so key indicators were within specifications. Table 8 shows a summary of the principal characteristics of the resulting design.

Table 8 Principal characteristics of the "center point" design for a notional offshore patrol vessel.

Principal Characteristics		
LWL	230.4	Ft
Beam	34.2	Ft
Depth, Station 10	18.5	Ft
Draft	11.0	Ft
GMT	3.7	Ft
Δ	1492	Ltons
GM/B Ratio	0.108	
C_P	0.62	
C_X	0.97	
Sustained Speed	25.0	knt
Endurance Speed	15.0	knt
Endurance	3780	nm
Number Main Engines	2	
Main Engine Rating	25000	hp
SHP/Shaft	25000	hp
Propeller Type	CRP	
Propeller Diameter	10.1	ft
Number SSGTG	3	
SSGTG Rating	1000	kW
Maximum Margined Electrical Load	1225	kW

As a final check of the baseline model, a “one at a time” approach was taken to varying the factors to ensure no wildly unrealistic parameters would be produced. Four of the five criteria (all but V_{MAX}) produced a design that could reasonably expect to be balanced with relatively minor adjustments to the above main design criteria. However, a V_{MAX} of 30 knots produced a required power that was more than double what two LM 2500 engines could provide, so it was decided to hold this variable fixed at the midpoint of 25 knots for all trials. The implications of this decision will be discussed in the analysis.

1. DOE: Factors and Responses

As discussed above, four of the five factors were used to test the response of the ship design model. Search speed was input as the endurance speed (V_E). The radar height and type were modeled on a combat system summary sheet, where the height was input as the desired height above the calculate draft, to ensure the predicted ranges would match those obtained in the operational model. The radar type was modeled by adjusting the weight of the antenna and control system with reference to the baseline as well as in reference to the power required by each of the systems.

The method used to estimate endurance merits some discussion. The amount of fuel onboard fixes a vessel’s maximum endurance, but it actually a function of many factors, such as specific fuel consumption based on engine type, total propulsive efficiency, generator load, *et cetera*. This leads to a challenging way of estimating exactly how to measure endurance in the model. The approach selected was to calculate the endurance in miles that the ship would effectively steam based on the endurance *time* and the search speed, which the model then uses to estimate the amount of fuel needed on board to achieve the required endurance. For example, at the midpoint, the search vessel would steam at 15 knots for 10 ½ days, which would be 3,780 nautical miles. Note that fuel for the ten-minute intercepts, transit to and from station, and an “operational reserve” amount are not included. However, neither is the operational use of engines, so for example, the model assumes both engines will always be used, but in all likelihood only one engine would be used at the slower search speeds, yielding a considerable improvement in fuel economy. The bottom line is that in order to avoid layering other modeling assumptions on top of assumptions, the endurance value was fixed in this way. It is important to note the key point here is to present an approach; a model of an operational fuel profile here would clearly add to the resolution of this particular model, but the author views this as not impacting the overall validity of the approach. Again, the point is not to design a ship, only to show how one might be designed.

The responses in the ship design were selected based on typical gross measurements of ship that a Naval Architect might be interested in. Specifically, Length at the Waterline (LWL), Beam (B), GM/B (a measure of stability) and Draft (T). Additionally, cost was selected as a sixth response, given that cost is always going to be a consideration in any design. The cost used for the model was "total lead ship cost," which includes estimates of government furnished equipment and cost margins. While "Total Ownership Cost" (or life cycle cost) is of a vital interest in today's U.S. Acquisition community, modeling it would require making assumptions, to include how many would be procured, an acquisition strategy, learning curves, and so on. Many of those assumptions can confound the cost of the ship if the actual acquisition strategy is not known, so to control for it, it is simply eliminated. If the strategy is known or can be modeled, it should prove to be just as effective a response as lead ship cost.

In this case, a given the mix of factors, factor types (continuous and categorical), and levels, a custom design was selected. Primary interactions and second order effects were desired in this particular case, which resulted in a design with 24 data points. Table 9 shows the experimental design.

Table 9 Experimental design for ship synthesis model.

	Design Factors			
Run	Endurance (NM)	Search Speed (kts)	Radar Height (m)	Radar Type
1	7	10	20	M
2	7	10	15	H
3	7	20	25	M
4	7	20	25	L
5	10.5	10	25	H
6	14	15	15	M
7	7	20	15	M
8	10.5	10	15	M
9	14	10	15	L
10	7	15	25	H
11	14	15	25	L
12	10.5	15	20	L
13	10.5	20	15	H
14	14	20	15	L
15	10.5	15	20	M
16	14	10	20	H
17	7	15	15	L
18	7	10	25	L
19	14	10	25	M
20	10.5	15	20	L
21	7	20	20	H
22	14	20	25	H
23	14	15	15	H
24	14	20	20	M

C. RESULTS

1. Initial Screening

Unlike the operational design model, each iteration only produces a point estimate for each criteria, and therefore obtaining the responses is far easier. For each trial, the factors were adjusted, the full load weight estimate was iterated until it matched the calculated weight, and the responses were recorded. Most of the resulting designs would be discarded as infeasible (largely because GM/B has a relatively narrow range of generally accepted values, between .09 and .122), but there were many that were close to that range, such that if other design factors not under consideration (and therefore held constant) were adjusted, a balanced vessel could be produced.

JMP produced a least squares fit model for each of the six responses, using all factors, with primary and secondary interactions. The R-squares, residual plots and other fit indicators all suggest a strong fit, and showed expected behavior. Figure 8 shows the prediction profile for the full screening model.

The next step was to refine the individual models for each of the responses based on the factors that were statistically significant. This step is two-fold; first it will yield mathematical models with a reasonable number of terms to incorporate in further spreadsheet modeling, and second it should reveal the key terms across all factors to develop a contour plot—again with a reasonable number of terms—to show all the interactions graphically.

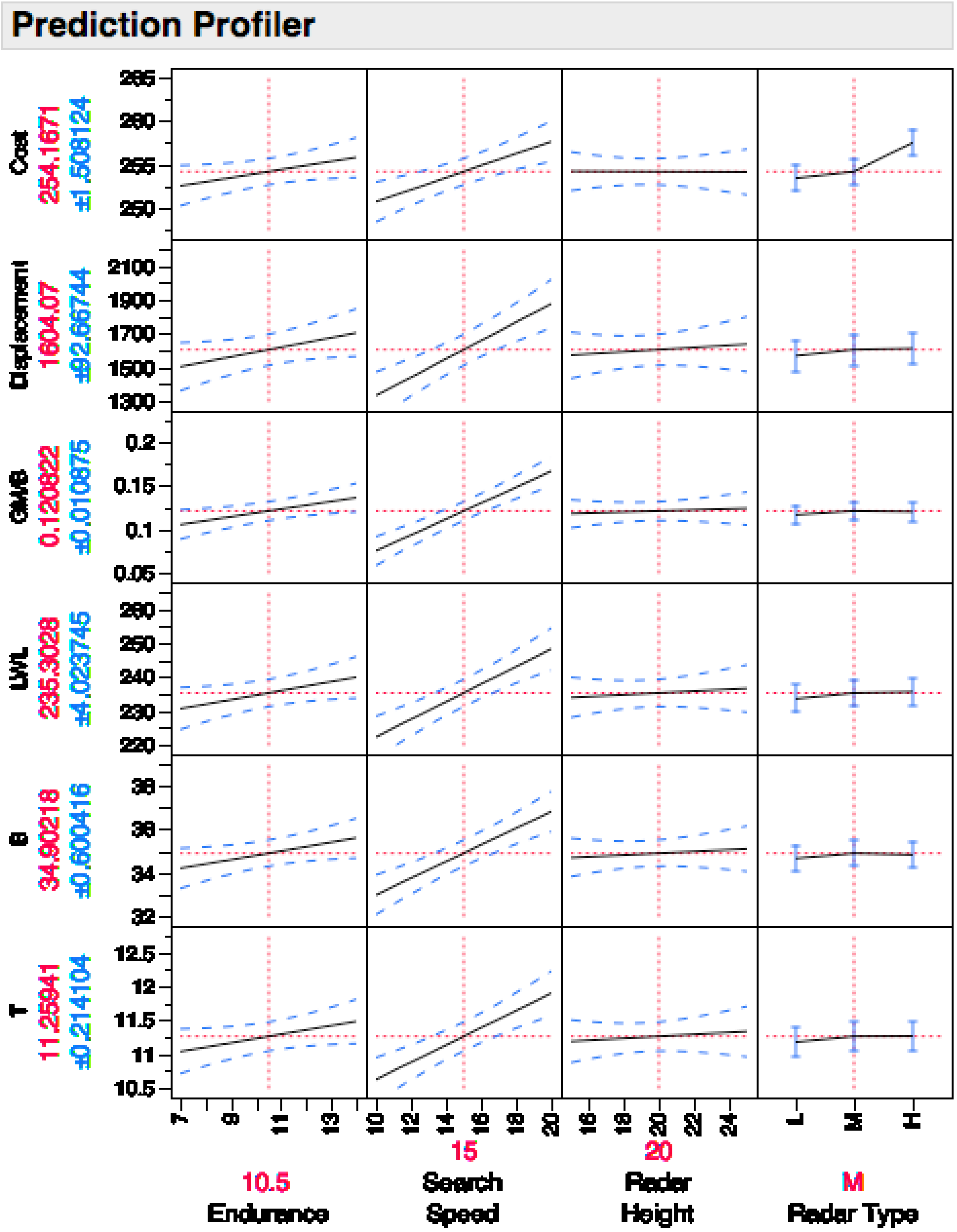
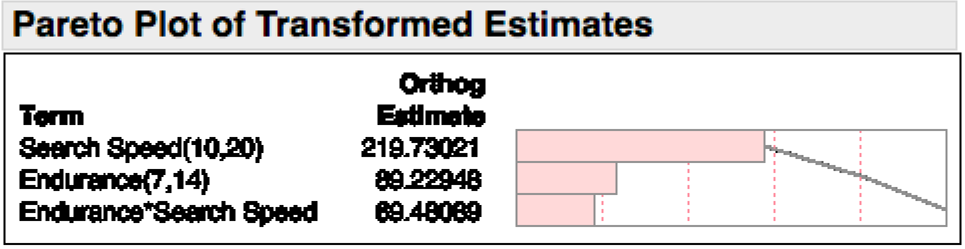


Figure 8 Prediction profile for screening model with all primary and secondary interactions of all factors set at midpoints.

a. Displacement As the Response

The statistically significant ($p < 0.05$) factors for predicting displacement include search speed, endurance, and endurance crossed with search speed. The resulting refined model has an adjusted R-Square of 0.9019, and shows no anomalies. The model is represented by Equation IV-1 (units removed for clarity but are indicated in Table 9 Figure 9 is a Pareto plot for displacement. Note that the next five Pareto plots are similar and are not shown.

$$\Delta = 1592.4 + 113.0\left(\frac{\text{Endurance} - 10.5}{3.5}\right) + 275.2\left(\frac{\text{Search Speed} - 15}{5}\right) + \left(\frac{\text{Endurance} - 10.5}{3.5}\right)\left(\left(\frac{\text{Search Speed} - 15}{5}\right) * 95.0\right) + \varepsilon \qquad \text{(IV-1)}$$



Pareto Plot of Transformed Estimates

Term	Orthog Estimate
Search Speed(10,20)	219.73021
Endurance(7,14)	89.22948
Endurance*Search Speed	69.48069

Figure 9 Pareto plot for displacement. Remaining Pareto plots similar.

b. GM/B As the Response

The statistically significant ($P < 0.05$) factors for predicting GM/B were again search speed, endurance, and endurance crossed with search speed. The resulting refined model has an adjusted R-Square of 0.9502, and shows no anomalies. The model is represented by Equation IV-2 (units removed for clarity, but are indicated in Table 9

$$\text{GM/B} = 0.119 + 0.0176\left(\frac{\text{Endurance} - 10.5}{3.5}\right) + 0.0465\left(\frac{\text{Search Speed} - 15}{5}\right) + \left(\frac{\text{Endurance} - 10.5}{3.5}\right)\left(\left(\frac{\text{Search Speed} - 15}{5}\right) * 0.0091\right) + \varepsilon \qquad \text{(IV-2)}$$

c. Waterline Length As the Response

The statistically significant ($P < 0.05$) factors for predicting length at the waterline were again search speed, endurance, and endurance crossed with search speed. The resulting refined model has an adjusted R-Square of 0.9171, and shows no anomalies. The model is represented by Equation IV-3 (units removed for clarity but are indicated in Table 9

$$\begin{aligned} LWL = 234.8 + 5.25\left(\frac{\text{Endurance} - 10.5}{3.5}\right) + 13.20\left(\frac{\text{Search Speed} - 15}{5}\right) \\ + \left(\frac{\text{Endurance} - 10.5}{3.5}\right)\left(\left(\frac{\text{Search Speed} - 15}{5}\right) * 3.93\right) + \varepsilon \end{aligned} \qquad \text{(IV-3)}$$

d. Beam As the Response

The statistically significant ($P < 0.05$) factors for predicting beam were again search speed, endurance, and endurance crossed with search speed. The resulting refined model has an adjusted R-Square of 0.9179, and shows no anomalies. The model is represented by Equation IV-4 (units removed for clarity, but are indicated in Table 9

$$\begin{aligned} B = 34.79 + 0.78\left(\frac{\text{Endurance} - 10.5}{3.5}\right) + 2.02\left(\frac{\text{Search Speed} - 15}{5}\right) \\ + \left(\frac{\text{Endurance} - 10.5}{3.5}\right)\left(\left(\frac{\text{Search Speed} - 15}{5}\right) * 0.59\right) + \varepsilon \end{aligned} \qquad \text{(IV-4)}$$

e. Draft As the Response

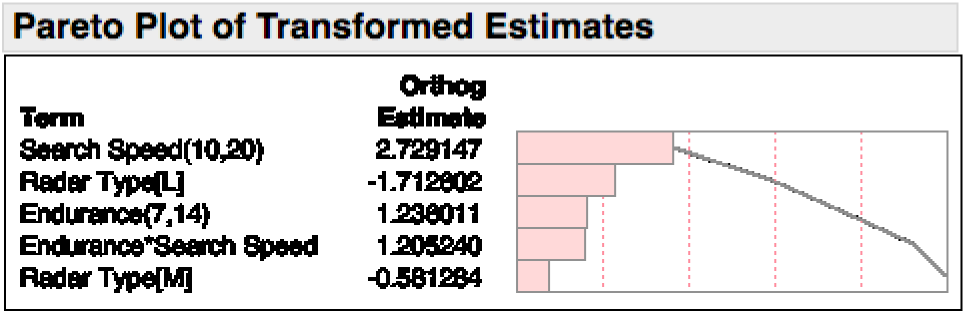
The statistically significant ($P < 0.05$) factors for predicting draft (T) were again search speed, endurance, and endurance crossed with search speed. The resulting refined model has an adjusted R-Square of 0.9302, and shows no anomalies. The model is represented by Equation IV-4 (units removed for clarity but are indicated in Table 9.

$$T = 11.23 + 0.25\left(\frac{\text{Endurance} - 10.5}{3.5}\right) + 0.65\left(\frac{\text{Search Speed} - 15}{5}\right) + \left(\frac{\text{Endurance} - 10.5}{3.5}\right)\left(\left(\frac{\text{Search Speed} - 15}{5}\right) * 0.19\right) + \varepsilon \qquad \text{(IV-5)}$$

f. Cost as the Response

The statistically significant ($P < 0.05$) factors for predicting lead ship cost (in U.S.$M) were again search speed, endurance, and endurance crossed with search speed. However, this time the radar type was also a predictor. This latter point is not too surprising since a portion of the total cost estimate is based specifically on the weight of the combat system. The resulting refined model has an adjusted R-Square of 0.8739, and shows no anomalies. The model is represented by Equation IV-4 (units removed for clarity, but are indicated in Table 9 Figure 10 is the Pareto plot for the cost model.

$$\$M = 255.00 + 1.53\left(\frac{\text{Endurance} - 10.5}{3.5}\right) + 3.44\left(\frac{\text{Search Speed} - 15}{5}\right) + \left(\frac{\text{Endurance} - 10.5}{3.5}\right)\left(\left(\frac{\text{Search Speed} - 15}{5}\right) * 1.58\right) + \begin{pmatrix} -1.69\ \mathit{for}\ "\mathit{Low}" \\ -0.82\ \mathit{for}\ "\mathit{Medium}" \\ +2.51\ \mathit{for}\ "\mathit{High}" \end{pmatrix} + \varepsilon \qquad \text{(IV-6)}$$



Pareto Plot of Transformed Estimates

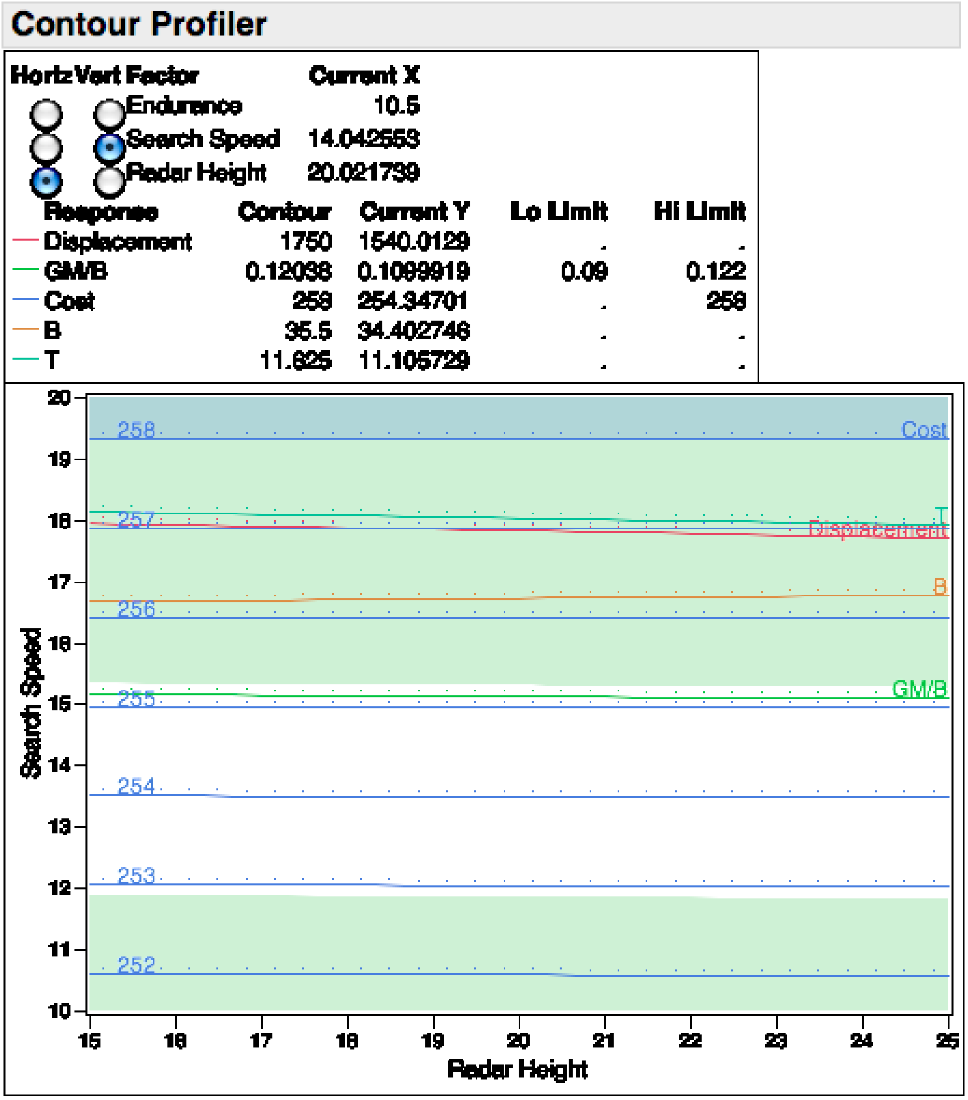
Term	Orthog Estimate
Search Speed(10,20)	2.729147
Radar Type[L]	-1.712602
Endurance(7,14)	1.236011
Endurance*Search Speed	1.205240
Radar Type[M]	-0.581284

Figure 10 Pareto plot with cost as the response.

2. Combined Ship Synthesis Model

The preceding sections identified the mathematical models for each of the 6 responses. This is appropriate for finding point estimates for performance in a spreadsheet, but an advantage of JMP is an ability to present all the responses graphically using a contour plot. To achieve this, a new model was created using only the four factors identified across all of the responses as statistically significant: search speed, endurance, search speed crossed with endurance (common to all six) and radar type (significant in the cost model only).

JMP's contour plot is an interactive tool that aids in decision making by showing interactions and highlighting feasible regions, among other things. Figure 11 shows a snapshot of one of an infinite number of contour plots. From this particular plot, search speed and radar height are shown on the x and y axis. Infeasible designs due to GM/B are shaded in green (leaving the white area as the solution space). A theoretical $258M cost cap is shaded in blue near the top. The contour lines for each of the responses (which appear straight largely because of the minimal sensitively to radar height in the ship design) can be adjusted by slider bars (which do not appear in the screen capture) or by typing exact numbers in the contour column. The "Current X" position can also be adjusted by slider, by moving a crosshair (not shown) or by manually typing a value. The Current Y shows the resulting values for each of the responses based on the Current X or the position of the cross hair. The full utility of this graph and how it can be related to the operational design will be shown in the following chapter.



Contour Profiler

Horiz	Vert	Factor	Current X
○	○	Endurance	10.5
○	●	Search Speed	14.042553
●	○	Radar Height	20.021739

Response	Contour	Current Y	Lo Limit	Hi Limit
Displacement	1750	1540.0129	.	.
GM/B	0.12038	0.1099919	0.09	0.122
Cost	259	254.34701	.	259
B	35.5	34.402746	.	.
T	11.625	11.105729	.	.

Figure 11 A sample contour plot for a combined ship synthesis model.

D. CHAPTER SUMMARY

This chapter introduced a ship design synthesis tool, an Excel spreadsheet that can be used to model various basic design considerations and costs associated with the construction of the ship. The factors that have been modeled thus far were re-introduced in the context of ship synthesis model, and an experimental design was presented to test the impact of those factors on five potential responses related to gross characteristics of ship design. A baseline ship was developed around the center points of the design factors that has roughly the same characteristics of a typical 1,500 tonne offshore patrol vessel. The results of the trials were presented, and six separate equations were presented. Also, a contour plot was presented to show the synthesis of the impacts of the factors on all six responses.

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V. LINKING THE OPERATIONAL AND SHIP SYNTHESIS MODELS

To this point, several mathematical and graphic models showing the factors and responses in an operational model and ship synthesis model have been presented. However, the two models have not been linked yet—the main objective of this thesis. This chapter will present two approaches to accomplishing that objective.

A. REVIEW OF RESULTS OF INDIVIDUAL MODELS

1. Operational Model

Five factors were considered for the inclusion in the operational model: radar type, radar antenna height, search speed, intercept speed, and endurance (time on station). These measures of performance were measured in a discrete event simulation using ExtendSim software of a Maritime Intercept Operation (MIO) scenario the Persian Gulf, with the objective of ultimately measuring the essential Measure of Effectiveness, probability of intercepting a target vessel, P(I). A statistically significant and valid model was found, with all but the radar type having statistical significance. The resulting mathematic model was presented in Equation III-1, and is reproduced here:

$$\begin{aligned} P(I) = 0.443 + 0.041\left(\frac{\text{Radar Height} - 20}{5}\right) + 0.19\left(\frac{\text{Search Speed} - 15}{5}\right) - \\ 0.009\left(\frac{\text{Endurance} - 10.5}{3.5}\right) + 0.007\left(\frac{\text{Intercept Spd.} - 25}{5}\right) + \varepsilon \end{aligned} \tag{V-1}$$

2. Ship Synthesis Model

An Excel-based model was used to first construct a baseline ship based on the center points of the same five factors. The notional vessel is similar in size and shape to the Róisín class of offshore patrol vessels in the Irish Navy. These factors were compared against six potential responses, five essential gross characteristics of a vessel (displacement, draft, beam, GM/B, and waterline length) and cost. Statistically valid models were found for a all six responses, with search speed, endurance, and the interaction between the two factors found to be statistically significant in all six models, and radar type additionally found to be significant in the cost model. Although not reproduced here, Equations IV-1 through IV-6 in the previous chapter are the mathematical models for each response. Further, graphical representations of the combination of effects were shown using a JMP contour plot.

B. COMBINING THE MODELS

Recall the primary objective of this thesis is to be able to show a decision maker the impact that ship design decisions have on an operational measure of effectiveness using various model-based systems engineering methods. This section seeks to present two ways of combining those models. The first is to create a "point solution" with the modeled equations as an extension of the Excel modeling tool. The second approach is to use the interactive graphing capability of the JMP software.

1. Mathematical Evaluation

Upon examination of all of the equation models, the first thing to note is that search speed and endurance are common to all of the equations. This should, logically, provide the common point of integration. However, there are some other relationships to note before examining that relationship further.

Radar antenna height contributes to the P(I). However, the impact on the design synthesis model is barely perceptible. This should not be surprising given a relatively small antenna on a relatively large ship. Next, the radar type only factors into the cost model. Again not surprising, as the weights are relatively insignificant, but since the cost estimate is weight based with a heavy emphasis on the combat system weights, it should be more sensitive to changes in those weight groups.

Finally, the intercept speed does play a small role in determining P(I), however it is excluded from the design synthesis model because the upper range of speed creates unfeasible designs; see the previous chapter for a more detailed explanation of this limitation. While it is reasonable to expect that the maximum speed should play a significant role in the design synthesis model, it is not the least bit surprising that it does not weigh too heavily in the operational model because of scenario setup. The patrol vessel is at the end of the run, in a “goal keeper” position. It should always have the advantageous position, having to execute with a good lead, almost never in a tail chase. Even a modest speed advantage would mean it could make the intercept.

Solving the above series of equations to produce a point solution is a fairly straightforward process. In the ship design model, there are two unknowns of statistical significance (endurance and search speed) and five potential responses related to the ship design, all in the form of

$$Y = \mu_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1 x_2 + \varepsilon \qquad \text{(V-2)}$$

where Y is the response of interest (GM/B, displacement *et cetera*), μ_0 and the β terms are the intercept and coefficients from the JMP model and are constant, and

$$x_1 = \left(\frac{\text{Endurance} - 10.5}{3.5} \right) \text{ and } x_2 = \left(\frac{\text{Search Speed} - 15}{5} \right). \qquad \text{(V-3, V-4)}$$

These are complex but linear equations, and with the help of a spreadsheet should be solvable, although not without some effort.

Prior to attempting to solve them, it is possible to look at a similar model that only accounts for first-order (primary) interactions, which create a series of simple, simultaneous linear equations without the β_3 term. Although any pair of response equations can be used, the two with the highest adjusted R-Squares were selected, those for GM/B and beam. These were easily solved for endurance and search speed in Excel, and should have produced similar values that were input, but they did not. After unsuccessful trials with other pairs of responses, it was finally discovered the solutions are hyper-sensitive to the coefficients, and altering even one coefficient by half of the standard error produced a wildly different outcome. It is possible to adjust the coefficients to achieve the desired outcome, but due to time limitations, a systematic, statistically sound way to do this without simply guessing was not practical.

The next step would be to solve the complex linear equations. As mentioned above, they are solvable, but with a considerable level of effort by hand and no simple approach in a spreadsheet. Further investigations of more precise mathematical relationships are beyond the scope and time available for this thesis.

However, let us assume for the moment that the simple model is accurate in estimating the endurance and search speed of the synthesized ship model. By "accurate," let us assume that the estimated endurance and search speed of a balanced ship model are within 10% of the endurance used in the operational model. It is now possible to substitute the endurance and search speed terms into Equation V-1 for the probability of intercept. The radar height does not impact the ship design model, and can be used directly. The intercept speed presents a problem that will be addressed below, but must be held constant at 25 knots. *Now, it should be possible to change any factor in the ship design—engine type, propulsive efficiency, design coefficients, and so on—and directly see how P(I) varies with changes in ship design.*

Given the inaccuracy of the predictive model as discussed, use of an excel spreadsheet to calculate results did in fact show the expected change in the operational MOE when a design factor was changed. Although exact numbers are not provided due to their inaccuracy, a trial change was made—specifically the propulsive efficiency was improved—and the resulting P(I) did increase as expected.

Intercept speed (or V_{MAX}) presents a problem because it will have an effect on the ship design. However, recall that it was held constant at the midpoint because it quickly produces an infeasible design due to power requirements at the upper bounds. Since it does have a measureable effect on the operational model and *should* have a significant effect on the design model, it should be held constant throughout varying any design parameters in this case. Alternatively, its impact on P(I) appears relatively small in spite of its statistical significance. In this particular case, intercept speed may be of no practical significance; as discussed early, the notional vessel has a superior speed and tactical advantage at the outset. The chosen speed of 25 knots is close to the maximum speed of the Róisín, and will easily accomplish the required tasks in this OPSIT.

2. Graphical Evaluation

The power of JMP's interactive contour profiler, however, can easily accomplish what is difficult and time consuming in Excel alone. There are a considerable number of ways it can be used, but to demonstrate its potential two in particular will be examined. Figure 12 and Figure 13 are snap shots of the following examples that can be referred to while reading the below description of how the models were set up.

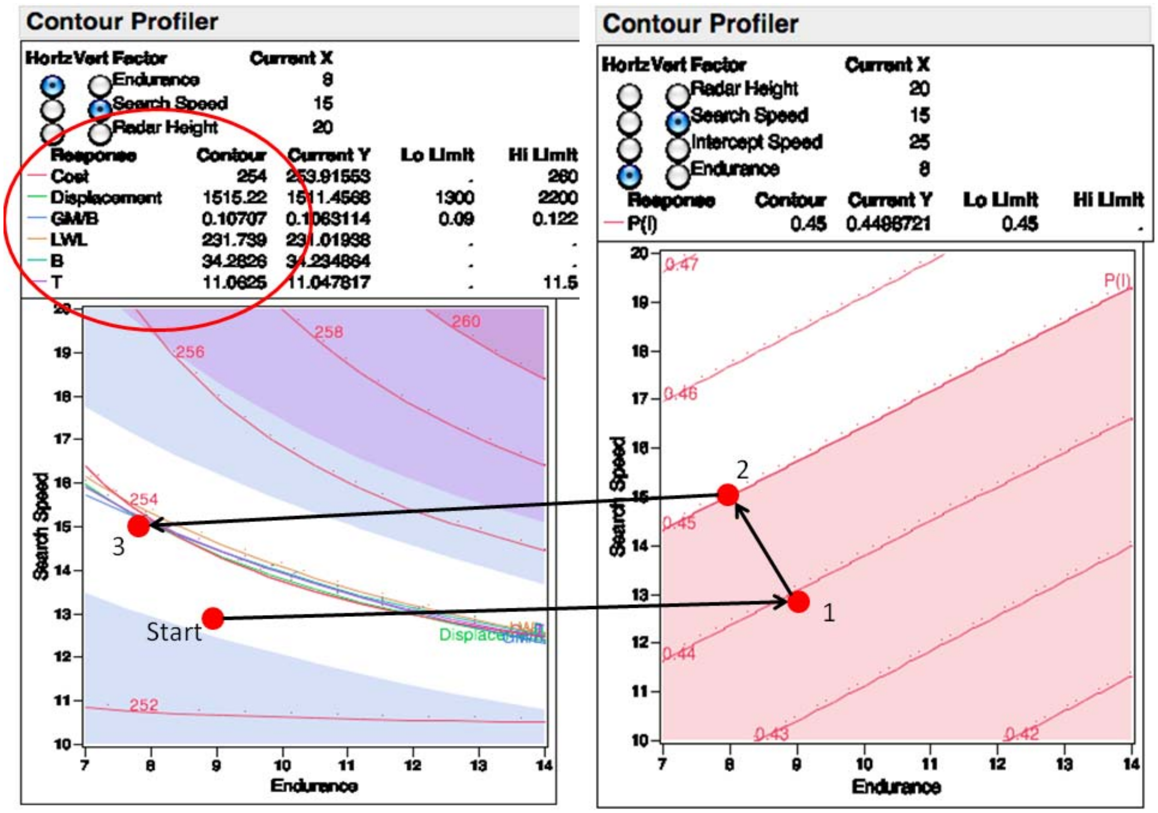
Once JMP builds the contour profile, the X- and Y-axes should be set to be identical in both plots. While not strictly necessary, it does make the graphical representation somewhat easier to understand. In this case, endurance was placed on the X axis and Search Speed on the Y. Those particular two were used because they are the two factors that are common to both models, but any pair can be chosen, largely depending on what particular factors require emphasis.

The next few steps should aid a decision maker with the use of graphic capabilities. Let us assume that in the design and acquisition process, the design is constrained to cost under $260M, GM/B must be between 0.09 and 0.122 (standard), the draft must be less than 11½ feet, and the minimum P(I) is 0.45. These numbers are placed in the respective Lo Limit and Hi Limit boxes. The infeasible regions are shaded out in the plot. Cost is always at the forefront of a decision maker's thinking, so let us also add cost contours to the ship design plot.

Before proceeding to the examples, there are a few immediate items that are shown immediately. First, the operational model contour tells us that moving up and to the left will increase the P(I). Second, GM/B is the most restrictive factor in the ship design model, and therefore all of the feasible designs will meet the cost and draft constraints. It is also important to note that changing the values of the factors that are not shown on either the x- or y- axes changes the contour plot itself; they are not simply ignored or treated as un-changeable constants.

a. Example 1: P(I) of a Given Design

The contour plot in JMP is a highly interactive tool which is impossible to completely recreate in static form, however, it will be helpful to refer to Figure 12 while reading. For example 1, the Naval Architecture team is assumed to have designed a ship with a sustained speed of 13 knots and a projected on-station time (endurance) of 9 days based on the engine configuration and projected propulsive efficiency (“Start” in Figure 1). Placing the cross hairs on the operational model shows that the resulting P(I) is only 0.44 (“Point 1”), below the threshold for that MOE (area is shaded). It then appears the closest point that will achieve the required P(I) is with an endurance 8 days and a sustained (search) speed of 15 knots (“Point 2’). The equivalent point back in the ship profile (“Point 3”) began in an infeasible region (shaded), but now the Naval Architect can adjust the sliders representing the other responses (circle area) to get an idea of target displacement, GM/B, LWL, *et cetera* to achieve the desired P(I). In this case, that is a displacement of about 1515 tons, GM/B of .107, LWL of 232 feet, B of 34.2 feet, and a draft of 11.1 feet. Note however that this does NOT assure a balance ship design; it only projects approximately where a balanced ship needs to be to achieve the desired P(I).



Contour Profiler

Horiz	Vert	Factor	Current X
●	○	Endurance	8
○	●	Search Speed	15
○	○	Radar Height	20

Response	Contour	Current Y	Lo Limit	Hi Limit
Cost	254	253.91553	.	260
Displacement	1515.22	1511.4568	1300	2200
GM/B	0.10707	0.1063114	0.09	0.122
LWL	231.739	231.01938	.	.
B	34.2826	34.234864	.	.
T	11.0625	11.047817	.	11.5

Contour Profiler

Horiz	Vert	Factor	Current X
○	○	Radar Height	20
○	●	Search Speed	15
○	○	Intercept Speed	25
●	○	Endurance	8

Response	Contour	Current Y	Lo Limit	Hi Limit
P(I)	0.45	0.4498721	0.45	.

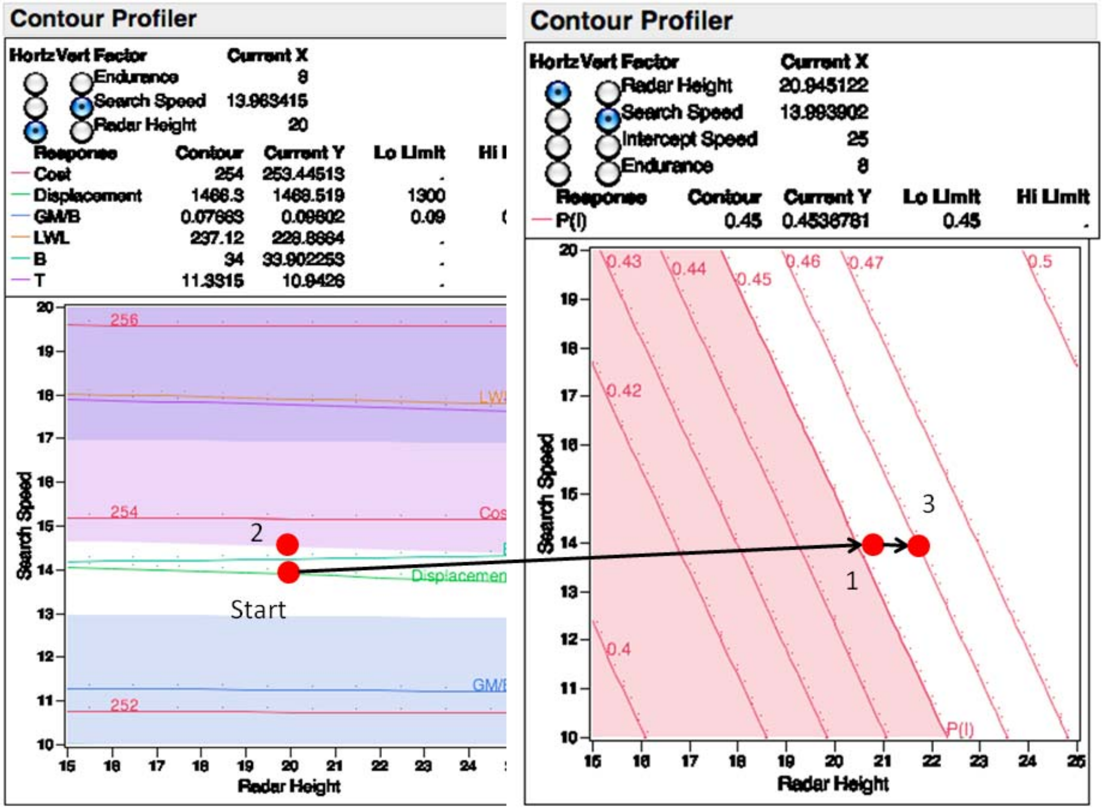
Ship Synthesis Model

Operational Model

Figure 12 Contour plot end states for Example One. See text for further explanation.

b. Example 2: Ship and Combat System Design Trade Off

It will again be helpful to refer to figure xxx while discussing this example. In this case, the X axes are set to show radar height, a factor that figures prominently in the operational model, but not the ship design model. The first change that is important to note is that now P(I) in the operational model improves as the design moves up and to the right in the model. Let us now assume that the draft has been constrained to 11 feet, which tightens the feasible region. The starting design uses an endurance speed of 14 knots with the radar antenna at 20 meters ("Start" point). The P(I) is predicted to be 0.446 ("Point 1"), which is below the threshold (shaded area) in the Operational model. The model suggests either increasing the endurance (search) speed or raising the radar antenna to achieve a desirable P(I). Increasing the speed beyond a ½ knot places the design in the infeasible region (“Point 2”) and is not practical, so the antenna height must be raised to 21 meters (“Point 3”). Also worth noting is that this model shows a measurable increase in cost to increase search speed, but an imperceptible change to adjust the antenna height, which is potentially very useful information for a decision-maker.



Contour Profiler

Horiz	Vert	Factor	Current X
○	○	Endurance	8
○	●	Search Speed	13.963415
●	○	Radar Height	20

Response	Contour	Current Y	Lo Limit
Cost	254	253.44513	.
Displacement	1466.3	1468.519	1300
GM/B	0.07663	0.09802	0.09
LWL	237.12	228.8664	.
B	34	33.902253	.
T	11.3315	10.9426	.

Contour Profiler

Horiz	Vert	Factor	Current X
●	○	Radar Height	20.945122
○	●	Search Speed	13.993902
○	○	Intercept Speed	25
○	○	Endurance	8

Response	Contour	Current Y	Lo Limit	Hi Limit
P(I)	0.45	0.4536781	0.45	.

Ship Synthesis Model Operational Model

Figure 13 Contour plot end states for Example Two. See text for further explanation.

3. Sensitivity and Risk

A sensitivity analysis and risk assessment was not specifically conducted for this example process, as it is beyond the scope of this thesis. However, it does bear some discussion considering model employment.

First, as what was seen in the mathematical approach, some coefficients are potentially hypersensitive to error. That error is inherent in the contour plots, although not graphically represented by JMP. Since the point of this model is not to design a specific ship, the risk of not testing for sensitivity is minimal. However, it would be wise to check for factor sensitivity, especially when a design is forced to be close to threshold values.

Further, it is important to remember that this meta-model is built on a stochastic discrete event simulation and a deterministic ship design model where the underlying relationships were based on data between World War II and the 1970s. The scale of the error that is consequently propagated is likely quite large, but the risk in this case is low, since no actual design is at stake. There are far more accurate means of modeling both major components of the meta-model, and in an actual application of this process, not only should more accurate models be used, but careful consideration should be given to error sensitivity of the model and the associated risk to the final design.

C. CHAPTER SUMMARY

This chapter demonstrates the main emphasis of this thesis. Specifically, it is shown that an operational model and a ship synthesis model can be linked in at least two ways. The first is using point estimates in a mathematical model solving a series of equations in one model and substituting the outcomes into another. While this method is possible, it was not practical using this particular scenario, likely due to the accuracy of the model and more importantly, the sensitivity of the coefficients. A second, graphical method using the contour plot capability of JMP software was presented. The latter approach has the weakness of not directly linking the two models together, but that ability is traded for the versatility the plots can be used to ask an endless variety of questions concerning design trade offs.

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VI. CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY

Over at least the previous two decades, the U.S. Navy has sought to review and update its ship design process, both in response to changing political and organizational environments and resulting from rapid increases in technological capability. The main objective has been to better understand the full design spectrum and implications of design decisions as early in the design process as possible. This research presents an approach to consider that looks at a combatant as a single total system that should be designed from the outset based on its projected operational environment.

For purposes of this research, it was assumed that a need for a small surface combatant (an offshore patrol vessel) had already been establish and verified as legitimate need to close an identified capability gap. The first step in the process is to identify the projected operational environment in *operational* terms. In this scenario, the patrol vessel would be tasked to conduct maritime interdiction operations in the Persian Gulf against smuggler using small wooded dhows.

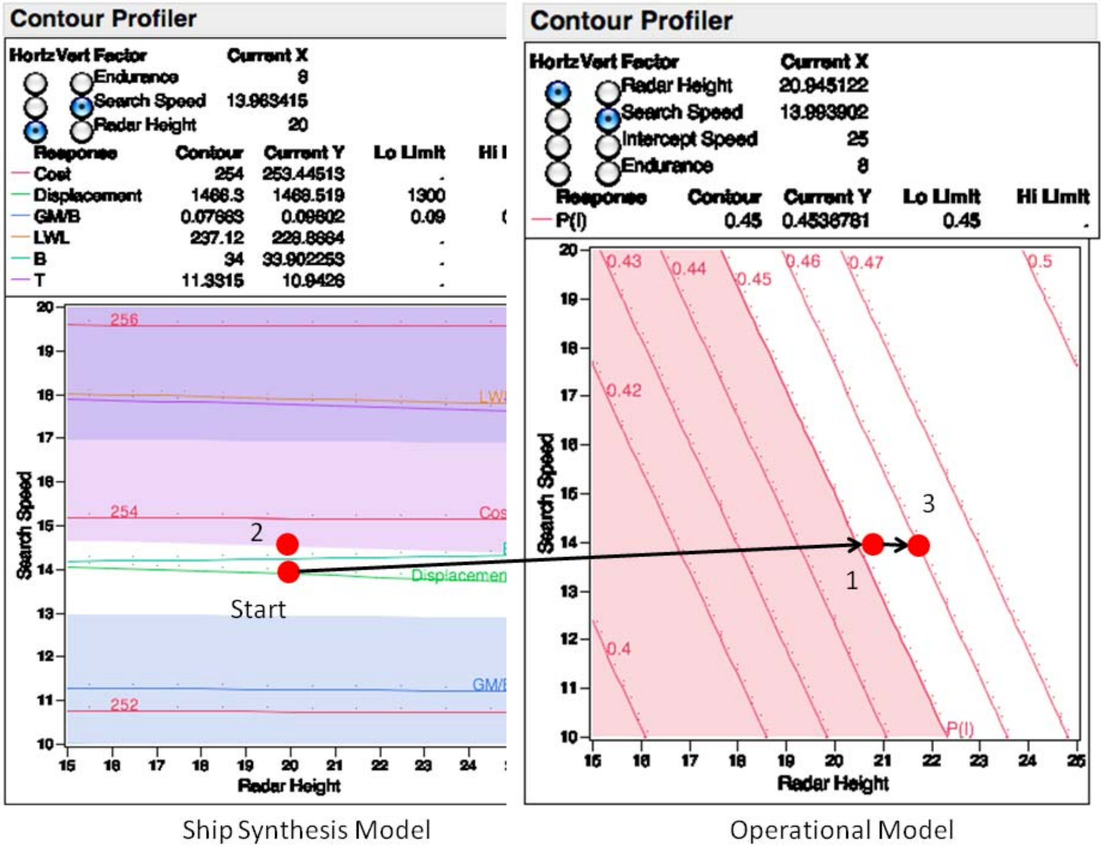
The actual design process begins with an operational model of the scenario, however the critical first step is to identify what operational measures of effectiveness that will be used to evaluate this platform. In this case, turning to the Universal Joint and Naval Task Lists, it was reasoned that there was only one critical MOE that could be mapped to basic ship design: probability of intercepting the target, or P(I).

The next step is to determine—from the field of Operations Analysis and from actual operator experience—what factors will influence that MOE. In this example, the outcome should be most heavily influenced by search speed, intercept speed, and radar sweep width. However, before the operational model is built, physics must inform how it is built. Vessel speeds are straightforward enough, but radar sweep width might be a function of either the masthead height or the performance of the radar itself. Another key step of this process is to capture those design considerations and build them into the operational model. Based on these decisions, the design space can be identified, a Design of Experiments can be built and run on the model, and a regression model is found. Continuing with this example, radar antenna height, intercept speed, search speed, and endurance were found to have a statistically significant impact on the response, P(I).

The next phase of this method is to apply the same approach to a ship design model, using a baseline vessel similar to the Róisín Class Patrol Vessel in the Irish Navy. For this exercise, a simple Excel spreadsheet was used as for a ship synthesis model. The same factors less intercept speed were used in a similar design of experiments approach was used. The resulting screening and regression model showed that endurance and intercept were the only two factors that caused a statistically significant response with five ship-design parameters (displacement, LWL, beam, GM/B, and draft).

There were two methods presented for connecting the two models. The first approach was to solve the equations from the ship design model for endurance and intercept speed and then substitute them into the operational regression model. The second approach was to place all of the factors and responses on JMP contour plots and graphically study how P(I) responds to changing input factors. Once this meta-model was constructed, it was then possible to show that a ship design parameter not directly related to the operational effectiveness could be changed and capture its *indirect* impact on the primary MOE, in this case P(I).

Figure 14 is a reproduction of Figure 13 in the previous chapter, which illustrates an example of how this tool might be used. The full explanation of the example is left to the previous chapter, but here it can be shown how two design considerations (radar height and search speed) can initially have an undesirable P(I). The contour plot on the right shows the viable options (go faster or raise the antenna). The plot on the left shows that cost takes an increase in search speed off the table. While this may be an intuitive example, it does illustrate the power of the method, specifically by being able to show how one changes effects other considerations immediately and interactively. And the method can also be used to explore and develop a better understanding of much more complex, less intuitive factor relationships.



Contour Profiler

Horiz	Vert	Factor	Current X
○	○	Endurance	8
○	●	Search Speed	13.983415
●	○	Radar Height	20

Response	Contour	Current Y	Lo Limit	Hi l
Cost	254	253.44513	.	
Displacement	1466.3	1468.519	1300	
GM/B	0.07663	0.09802	0.09	
LWL	237.12	228.8664	.	
B	34	33.902253	.	
T	11.3315	10.9426	.	

Ship Synthesis Model

Contour Profiler

Horiz	Vert	Factor	Current X
●	○	Radar Height	20.945122
○	●	Search Speed	13.993902
○	○	Intercept Speed	25
○	○	Endurance	8

Response	Contour	Current Y	Lo Limit	Hi Limit
P(I)	0.45	0.4536781	0.45	.

Operational Model

Figure 14 Illustration of "example 2," taken from the previous chapter.

B. CONCLUSIONS

From Chapter I, recall the research questions that were posed:

Primary Question:

Can a process to design a ship be shown that includes the linkages between traditional First Principles of Naval Architecture to mission effectiveness?

Secondary Questions:

Can an operational model of a Maritime Interception Operations (MIO) be developed that can show the potential mission effectiveness of a design concept?

Can a ship synthesis model be developed that can model the design responses to similar factors as the operational model?

Can the two models be linked in a meta-model to show linkages between ship design considerations and operational performance?

I will address the secondary questions first, and then answer the primary questions. Chapter III (as augmented by Appendix A) demonstrated the development of an operational model of typical MIO mission based on a believable Design Reference Mission. The factors tested for response demonstrated expected behavior, and the resulting mathematical model was statistically valid and significant. Therefore, the answer is yes, such an operational model can be built.

Chapter IV demonstrated the use of an existing low-fidelity Excel-based ship synthesis model to first "build" a baseline ship of a believable nature, and then show how the ship respond to the same operational design factors. Again, the responses were expected and reasonable, and it was statistically valid and significant, so yes, such a ship design model can be built.

To the third question, Chapter V showed two methods that both models could be linked. The first was a mathematical approach. While it was not accurate, likely due to the fidelity of the model and the lack of time to refine the mathematical solution, it was still functional in that a change to one of the non-tested factors in the ship design (such as propulsive efficiency) could show an expected numeric change to the operational measure of effectiveness. The second method demonstrated a graphical approach using the contour profiler in the JMP software that can easily be used to demonstrate the links between ship design factors and operational performance, at the expense of a direct linkage of the two models. Either of these approaches would be considered a meta-model, so yes, one can be built.

The answers to the secondary questions should have demonstrated that the answer to the primary question is clearly "yes." With the use of lower-level models, and meta-models that link them, the traditional roles of a combat systems engineer and a naval architect can be linked such that there can be an immediate demonstration of the effects of *ship design* on the overall measures of *operational effectiveness*, which should be the goal of any well-designed system. QED.

C. RECOMMENDATIONS FOR FURTHER RESEARCH

As a “proof of concept” mode of research, this creates a robust list for further investigation. What follows are some of the more significant areas that bear further investigation.

To keep the modeling requirements simple, the scenario was restricted to a simple mission and a simple ship. This portion of the scenario is not wholly realistic, as it is unlikely for any navy to desire a “one trick pony” in a ship. The next logical step in this research would be to first apply the same process to a more complex scenario—such as those developed by Gomes-Torres—and apply them to a more complex ship. These methods could easily be applied to a larger ship, such as a destroyer as well.

A limitation in this thesis was the ability to use a full response surface method in modeling either design. This is due entirely to the nature of the radar type that was modeled. Response surface methodology (to produce a true response surface) requires all the factors to be continuous, and the radar type variable is categorical. To better understand the impact of the radar on the ship design, it would be necessary to equate radar parameters (frequency, bandwidth, antenna aperture, *et cetera*) to ship design factors, specifically weight. Once that is done, radar type should be able to be modeled as a continuous variable. If that is achieved, instead of modeling three types of radar, the designers can more directly see how changes in radar factors impact both probability of detection and ship design, and then an optimum radar could be designed at the same time as the ship (rather than being forced to pull a system “off the shelf”). This approach would significantly improve the ability to design the total ship simultaneously.

There is considerable room to explore the methods of linking the models into meta models. First, it is possible to solve the linear equations to show the point solutions. Second, there are other software programs that can be used to link models in different software packages. It should also be possible to build one experimental design in which all of the responses in both models are collected together, treating it as one model from the beginning rather than trying to join to models after the fact. This proof of concept did not do that specifically as a risk-mitigation measure in order to enable trouble shooting of one model if need be. It is not appropriate to simply merge the data—a new experimental design would need to be developed and tested with all responses included.

As previously discussed in Chapter III, further research should be directed at determining a more exact answer to the level of fidelity of operational models required to present an accurate solution. While this thesis suggested that radar antenna could be a suitable surrogate for radar range performance, the author's personal experience suggests otherwise. This is likely because of the simplifying assumptions for attenuation and system losses, which can be particularly dramatic in the Persian Gulf.

Also along the lines of model fidelity, this particular operational model did not include any white, or neutral shipping or more than one patrol vessel conducting operations. Further, other detection and classification systems such as the Automated Information System (AIS) were not included since their weight is negligible (less than 20 pounds total), which would increase the P(D) and correct classification, especially if white shipping is included.

Finally, this thesis did not address factor sensitivity, risk, or cost variation at all. While the emphasis of this research was on the process and not on the output, it was clear at the back end of the process, factor sensitivity cannot be ignored.

APPENDIX A: UNDERLYING COMPUTATIONS IN THE OPERATIONAL MODEL

A. DETERMINING SWEEP WIDTH

The operational model was developed by the author using ExtendSim, and as such the underlying math should be documented. The basis of the operational model comes from Wagner, Mylander and Sanders (1999) and Washburn (2002). The math models used for radar performance come from Harney (2010).

The Radar Height limitation equation used (Harney, 2010)

$$L = 4.122H^{\frac{1}{2}}, \text{ H in meters} \tag{A1}$$

The radar horizon was determined by solving for L using the height of the radar and the height of the target, then summing them.

The basic radar range equation was used in the form (Harney, 2010):

$$CNR = \frac{\pi P_T L_T L_R D_T^2 D_R^2 \sigma}{64kTBF\lambda^2} \frac{e^{-2\alpha R}}{R^4} \tag{A2}$$

Where: CNR is the Carrier Noise Ration, P_T is transmitted power, L_R and L_T are loss figures for the transmitter and receiver, D_T and D_R are the transmit and receive antenna diameters, σ is the target cross section, k is Boltzmann's constant (1.38×10^{-23} $m^2kg/s2^K$), T is equipment temperature (used 290K), B is the beam width, F is the Noise Figure, λ is the wavelength, R is range, and $e\text{-}^{2\alpha R}$ is the atmospheric extinction factor. To solve for range in closed form, extinction is assumed negligible and set to unity. Also, the loss factors are generally not available for sample radars and are relatively insignificant, and are therefore also set to unity, and only radars with common transmit and receive antenna will be used. Solving for Range:

$$R = \left[\frac{\pi P_T D_A^4 \sigma}{64kTBF\lambda^2 \bullet CNR} \right]^{1/4} \tag{A3}$$

To estimate target cross section, the following equation was used:

$$\sigma = \frac{4\pi A^2 \rho}{\lambda^2} \tag{A4}$$

Where A is the area of the target, ρ is the reflectance, and λ is the wavelength. For a wooden target, the emissivity is assumed to 0.9, leaving the reflectance to be 0.1. The radar cross section of the target is updated for each radar in the model.

For the range to be useful, a realistic CNR must be assumed. To estimate this, Swerling II statistics were used for a moving target using Figure 15 Although this was built into the model as a user to provide additional functionality, it was held constant at 31 dB throughout all experiments. This figure is based on a probability of detection of 0.99 with probability of false alarms of 10^{-6}, shown by the dashed red line in Figure 15 .

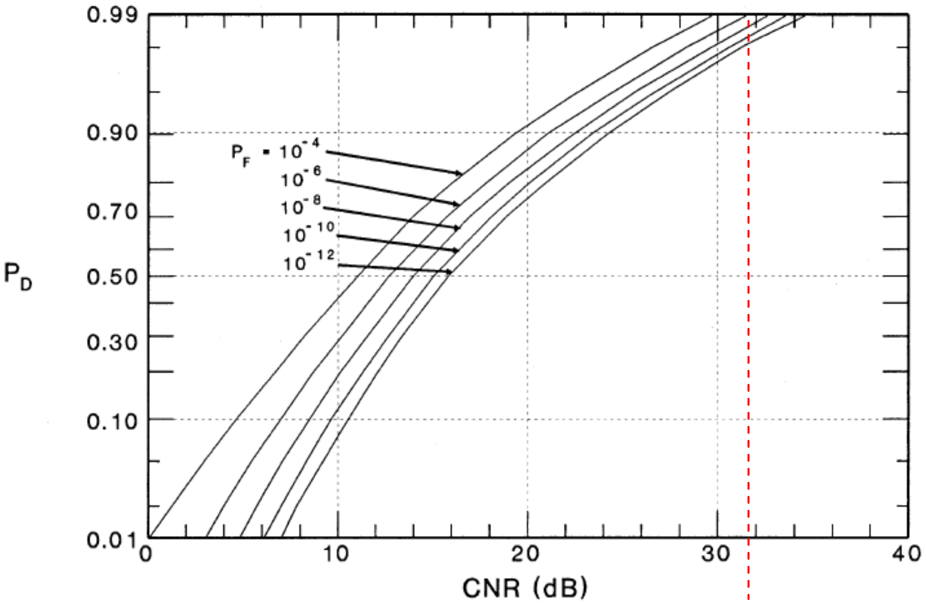


Figure 15 Receiver operating characteristic for Swerling II Statistics. (After Harney, 2010)

One the radar range was estimate based on the radar height and radar characteristics. The he two ranges were compared and the lesser number was chosen. The range was then doubled to represent the sweep width of the radar in other calculations.

B. TARGET GENERATION

The majority of the target is input by the user from the ExtendSim Control panel, however, there are some underlying assumptions in the model. First, it is assumed the target is made of wood. This is relatively easy to adjust in future versions of this model, however it was left as is for simplicity.

The user inputs the size of the target which is used in the radar height and radar cross sections above. However, the target speed that is entered is meant to represent an "intelligence estimate." Once that speed is entered, the model will actually create a target with a random speed based on a normal distribution with a mean set to the "intelligence estimate" and a standard deviation of one (assuming fairly good intelligence). This distribution is not adjustable from the workbook, but is reasonably easy to adjust in the model itself.

The target moves through a box that is created using the boundary height as the width and the length, entered in the workbook. The box is notionally horizontal, parallel to a Compass Course of 090° to keep the trigonometry used in the motion model simple, however as long the box is kept a true rectangle, in can simulate any heading orientation. The targets initial position is randomly selected somewhere along the western boundary of the box using a uniform distribution with the upper and lower bounds set to half the boundary width (thereby centering the rectangle on the x axis). The initial course is randomly selected such that the equivalent "True Course" of 090° with a standard deviation of 10° (i.e. the target will tend to track parallel to the axis of the box).

To simulate motion, a logic chain is used. First it determines if the target is within the search vessel's radar range. If it is, it is moved to the intercept phase, which is described below. If it is not, the target is moved towards its goal of exiting the eastern end by one minute using trig functions. If the target reaches an edge of the box, it is turned so that it stays inside and proceeds towards its goal. If the target reached the eastern edge of the box, it was deemed to have evaded detection, and was captured in the model database.

Targets are created at random times using an input from the workbook. Based on how ExtendSim creates targets, this is expressed as the average frequency targets attempt to "run" the boundary (i.e., "1" is once a day, "2" would be every two days, "0.5" is twice a day, *et cetera*). For this simulation, 1.2 runs per day was selected.

C. SEARCH METHOD SELECTION

The decision model for choosing the crossover or linear barrier patrol was made based on the predicted probability of detection for each method as computer in Naval Operations Analysis (Wagner et al.). This prediction of probability of detection is overly optimistic because it assumes a target traveling parallel to the axis of the boundary at a set speed. Recall from above that the actual speed of the target is a random variable based on the "intelligence estimate," further lessening the efficacy of the prediction. However, that is the nature of theoretical tactics versus the execution of the mission; the patrol vessel will make the best tactical decisions based on the information it has available to it.

The specific formulas used to predict detection probability follow. The development of these equations is left to the text of Naval Operations Analysis (Wagner, Mylander, and Sanders, 199), as it is too lengthy to reproduce here. For the crossover patrol:

$$P_{crosover} = \min\left\{1, \left(1 + \frac{\rho\sqrt{\rho^2 - 1}}{\rho + 1}\right)\frac{1}{\lambda + 1}\right\} \tag{A5}$$

Where ρ is the ratio of the patrol vessel's search speed and the predicted target's speed and λ is the ratio boundary width less twice the sweep width to the sweep width.

Similarly, the linear prediction was predicted using:

$$P_{linear} = \begin{cases} 1 - \left(\lambda - \dfrac{\sqrt{\rho^2 + 1} - 1}{2} \right)^2 \dfrac{1}{\lambda(\lambda+1)}, \text{ if } \rho \le 2\sqrt{\lambda(\lambda+1)}, \\ 1, \text{ otherwise.} \end{cases} \quad \text{(A6)}$$

The two probabilities were compared, and the method with the higher probability of detection was selected. If they were equal, the linear patrol was given preference.

D. PATROL VESSEL MOTION AND INTERCEPT MODELING

The patrol vessel was created using a "resource item" in ExtendSim. The resource was held to only one patrol vessel so that future versions of the model could be adapted to show the effects of multiple patrol vessels, however the motion model would require modification before that could be achieved.

The patrol vessel's motion was modeled similar to how the target vessel's motion was modeled above, with one notable exception. Based on the search method selection chosen above, there are two possible branches within the motion model; one for the crossover relative motion and one for the linear motion. The actual motion was again controlled by logic statements, where each minute of the simulation the patrol vessel would first check if it was in change of the target vessel, and if not would be moved according to a Boolean logic check of where it was in the box. If it "detected" the target, it was split off and "batched" with the target vessel.

Once the two were batched, the model immediately computed the ability to intercept the vessel. Although it is possible to mathematically predict an exact intercept point using speeds and course, the math involved in doing so is computationally intense, and in the interest of keeping simulation run times to a minimum, a conservative alternative method was derived. Note also that target vessels could continue to move through the box undetected while the intercept and boarding was occurring.

Specifically, the model would first calculate how long it would take the target vessel to get to the point of exit on its present course and speed, capturing the x,y position of that exit point. It would then calculate the time it would take the patrol vessel to get to the same point using the user-inputted intercept speed from the work book. If the latter time was smaller, it was assumed that the patrol vessel could make the intercept.

If the intercept was possible, the two vessels were paired in a “Boarding Activity” that would add a delay for the intercept, boarding, escort, and reposition. The length of the delay is set in the notebook. For this simulation, the boarding delay was somewhat arbitrarily set to 130 minutes, although in retrospect this is likely too low a number.

Once the boarding was complete, the target and patrol vessel were un-batched, the target was classified as having been “diverted,” and the patrol vessel was instantaneously returned to it’s start position to search for a new target. If an intercept was not possible the target vessel was immediately sent back to its start position, and the target vessel was classified as having “evaded.”

APPENDIX B: EXTENDSIM SCREEN SHOTS

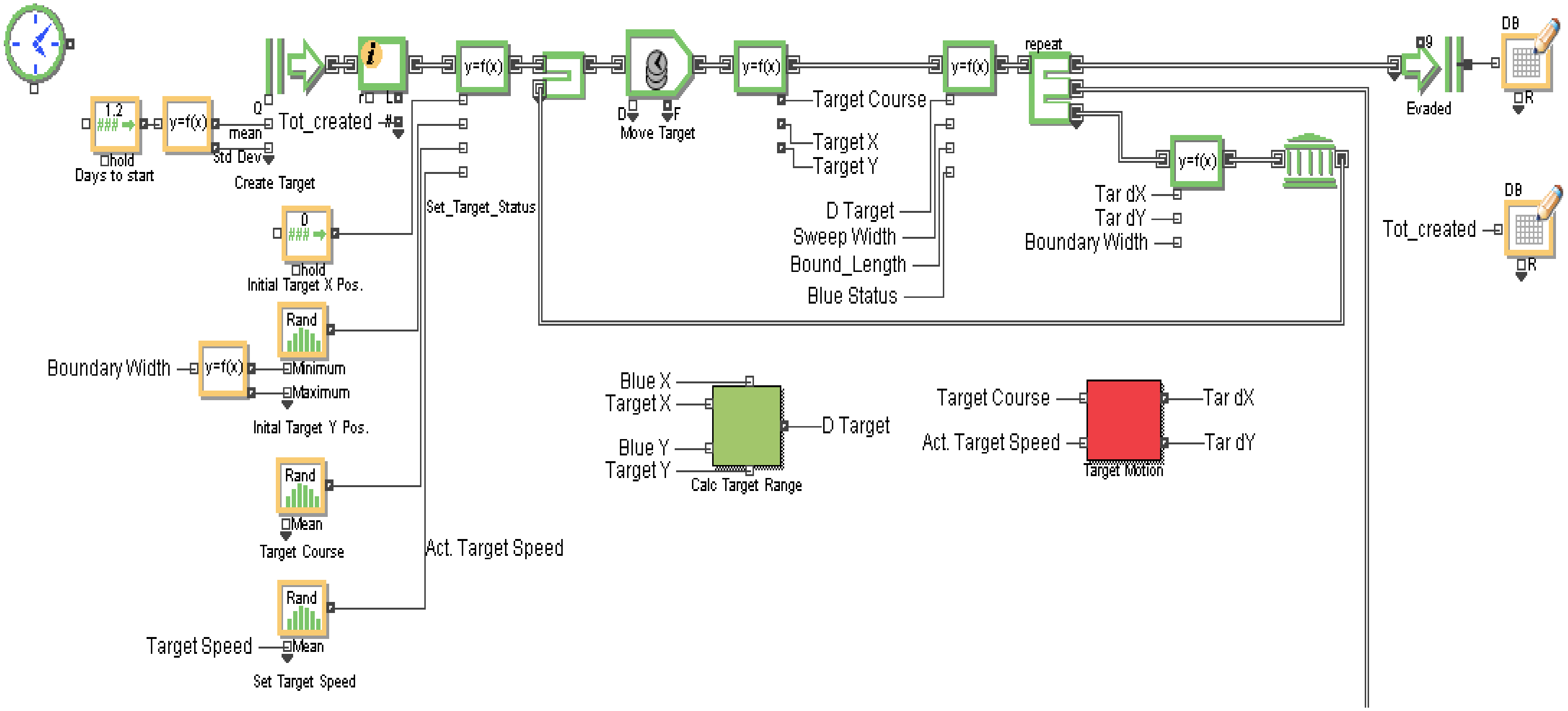


Figure 16 Target Section.

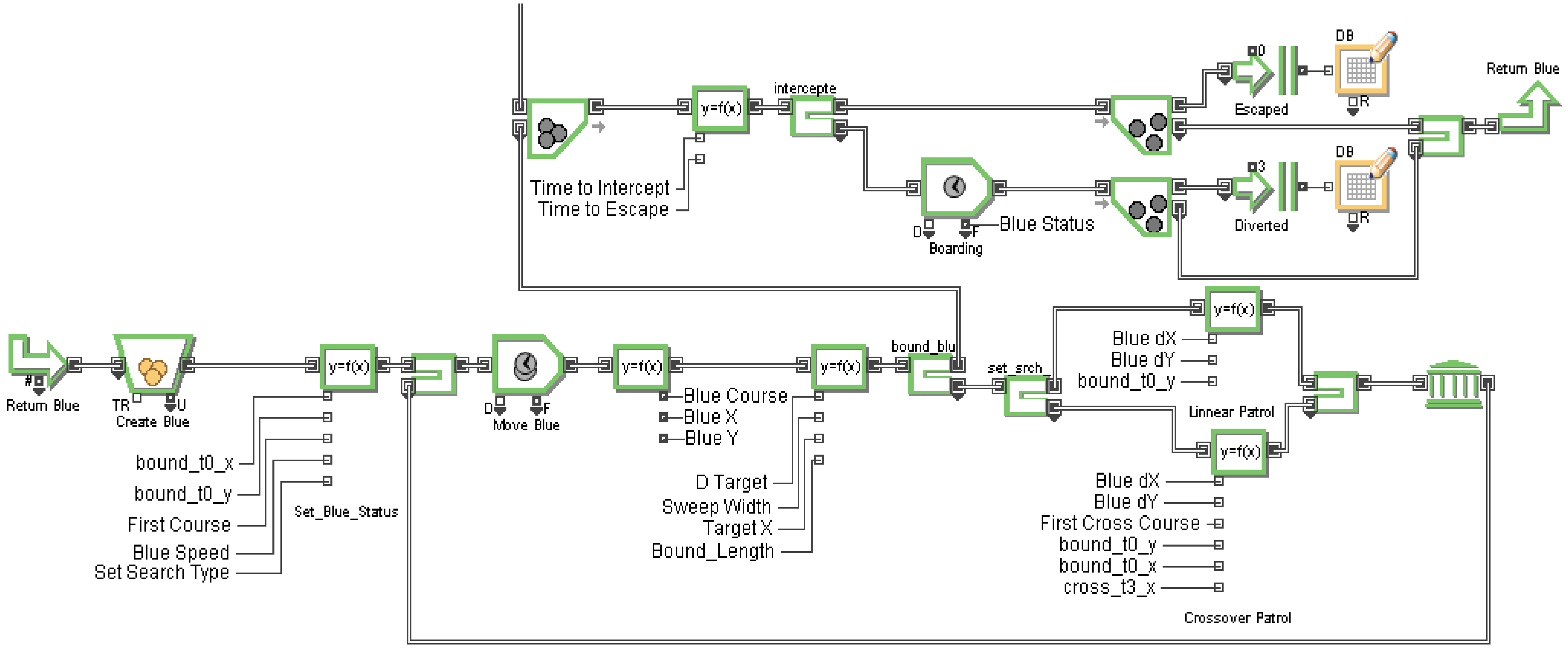


Figure 17 Patrol Vessel Motion (bottom section) and intercept/boarding section (top).

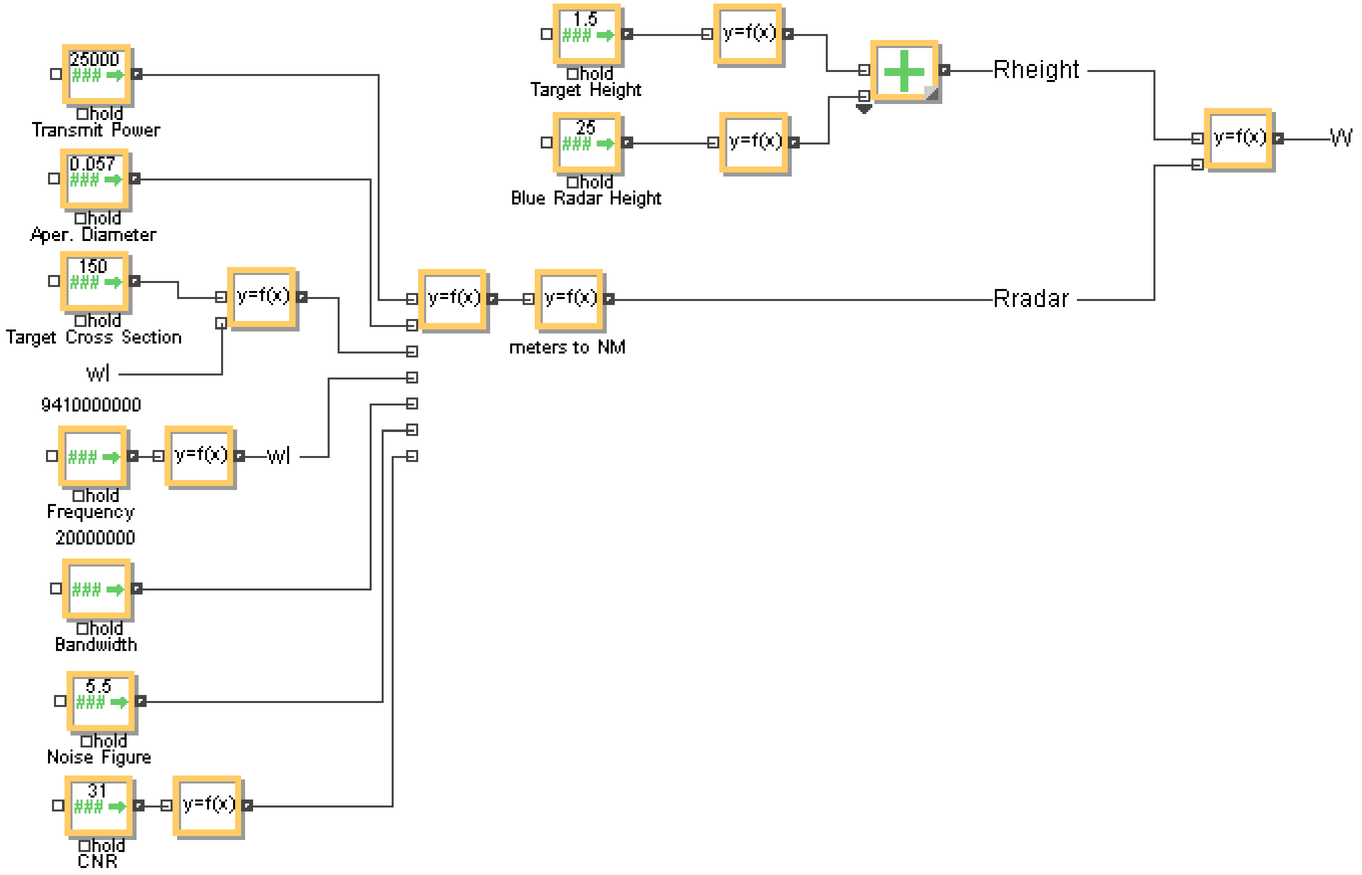


Figure 18 Radar Range prediction and decision.

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APPENDIX C: RADAR PARAMETERS

Parameter	**“Low End”**	**“Mid-Range”**	**“High-End”**
Frequency	9,410 MHz	3,050 MHz	10 GHz
Bandwidth	20 MHz	27 MHz	3.33 MHz
Aperture Dia.	.057m	0.385m	0.2284
Noise Figure	5.5dB	5.5dB	5.5dB
Power Out	25 kW	30 kW	1.2 kW
Approx. Ant. Wt.	125 lbs	300 lbs	2,000 lbs
Predicted Range	15.9 NM	32.5 NM	47.7 NM

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